NEW WORLDS:
COLONIZING PLANETS, MOONS AND BEYOND

Dan Răzvan Popoviciu

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New Worlds: Colonizing Planets, Moons and Beyond

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PREFACE

Be fruitful and increase in number; fill the earth and subdue it

Genesis, 1:28

Have you ever thought about what makes us, Homo sapiens, so special?

We are not particularly massive nor fast; we do not excel in terms of force or other natural features (claws, teeth, armor...). However, we are versatile, intelligent, and imaginative, with the unique ability to anticipate the future.

And there is more... We have a unique way of interacting with our environment. While any other animal would simply follow natural selection, living and evolving, breaking up into many new species, one for each environmental niche, or simply vanishing, leaving just some fossils, we chose another path. Our intelligence and versatility allow us to change the environment to suit us.

We ploughed the fields and grew livestock. We built villages and cities. Roads and irrigation canals. We ventured through the seas and atmosphere. We drilled into the depths of the Earth, to get useful resources. We created an industry, then, not long after, we stepped into the Post-Industrial Era: that of informatics and high technology. We wanted to know our environment, and we did it in order to tame it.

Maybe the most obvious consequence of these actions is that we are currently a planetary species. And this is not easy! Most species, microbial, vegetal or animal, are distributed only in a limited area here on Earth, with relatively homogenous living conditions. What other being do you know that is able to thrive from the frozen wastelands of Greenland to the Sahara and from the Tibetan Plateau to the Amazon rainforest? The few species close to this achievement are our parasites, crops and livestock!

Today, there is no corner of Earth where our traces are not visible. We are so "pro-eminent" that we even change the world's climate. More and more call the current climatic era the Anthropocene – the Human Epoch. Is this a good thing? A bad one? Only time will tell...

What is quite clear is that our species is difficult to eradicate. I know that the mass media regularly comes up with catastrophic scenarios, and that (post)apocalyptic novels and movies are popular (I am quite fond of, I admit!). Global nuclear war, unprecedented plagues, asteroids, super-volcanoes, or simply our indifference towards environmental degradation. The sad thing is that all these scenarios are plausible.

The good thing is that no matter how many millions die, a Global species dies hard. We are no less than 7,902,594,207 individuals on Earth while I write this paragraph (at least this is what one of the many dedicated online applications tells me [1], surely other apps give other numbers). While I finished writing the phrase above, 300 new earthlings were born!

Let's imagine extreme climate warming! Hey, but we can simply move towards the Poles, and we will survive! An ice age? We might just group together near the Equator. A super-pandemic? It would surely decimate urban and other densely-populated areas, but it is unlikely to reach isolated communities in the Arctic or Papua.

Certainly, this does not mean that we are invulnerable. A supernova in our "close" proximity would give us a shower of gamma rays, sterilizing all landmasses and surface waters. A black hole would swallow us, together with the whole planet. Even if we avoid such dangers, in about one billion years, the Sun will "swell", as its hydrogen reserves get exhausted, turning our home into molten rock. The Universe is a dangerous place where anything can happen.

Do you think I look too far into the future? To much to anticipate when, maybe after a day of hard work, you get home and open this book? You feel that it does not concern you?

Well, you should know that even though extinction is not imminent, an unprecedented crisis is still at our gates! Because we have reached a limit.

CONSENT FOR PUBLICATION

Not applicable.

CONFLICT OF INTEREST

The author confirms that he has no conflict of interest to declare for this publication.

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Declared none.

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CHAPTER 1

Crisis

Population, when unchecked, increases in a geometrical ratio.
Subsistence increases only in an arithmetical ratio.
Thomas Robert Malthus

Abstract:

More than 7.9 billion people currently inhabit Earth, and the population is growing. Halting this growth, although possible, would lead to Global economic and social collapse. Furthermore, the modern economy has a constantly growing demand for resources. Finally, demographic growth is inextricably linked to overall progress. Continuous growth *versus* a limited living space on Earth leads to an unavoidable crisis.

Keywords: Demography, Growth, Malthusianism, Progress, Resources.

1.1. A BIT OF DEMOGRAPHY

That Earth's human population constantly increases is surely no surprise for my readers. According to the current projections, there will be around 10 billion people by the end of this century (Fig. **1.1**).

Is it a big number? Many would say so, and overpopulation is a recurring theme in contemporary public discourse. Others would deny it. A popular meme plots the global population against its density. Briefly, a computer simulation shows that, at an overall density similar to that in New York City, all *Homo sapiens* individuals on Earth would easily fit in Texas (about three times the size of Romania), leaving the rest of the planet deserted [1]!

This is, surely, a valid point of view, just that our problem is not yet that of actual living space. This means we do not need to be afraid that we won't fit on Earth. The real problem concerns resources. No matter how we measure it, Earth's arable land is finite, to give just an example. As the population grows, its area per capita decreases. It is easy to imagine that, in a no so distant future, food production will become insufficient.

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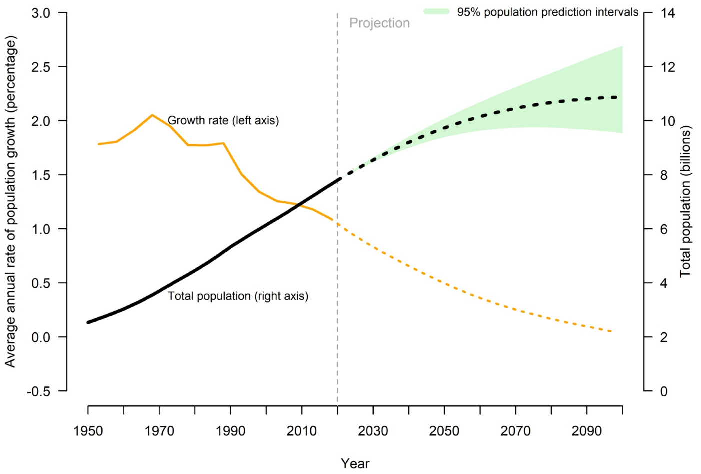

Fig. (1.1). Projected growth of Global human population until the end of the XXIst Century [2].

Other finite resources that will cause long-term problems are drinking water and mineral resources. When will they get depleted? Prognosing can be tricky, as the Club of Rome showed us (in 1972, they published a series of apocalyptic predictions for the next future; the next future became present and even past, and predictions did not come true). Still, the idea of finite resources *versus* a growing population is valid.

Throughout history, natural means of demographic regulation functioned. They include plagues, famine, wars *etc.*, basically, mass mortality events. How do you like those? Most contemporary people would consider such events unacceptable for an advanced society, and considering democratic and humanist values.

But the issue remains the same. Someone said that condemning humankind to a perpetual existence within the "borders" of this planet is a Fascist way of thinking. This because the next logical step is to decide who do we have to kill, for the rest of the population to continue living on the same resources.

Is there any alternative? Sure! Even more of them...

Can we stop demographic growth? Can we reach a perfect balance between birthrate and deathrate, one that should stay constant forever? Yes, in theory. If you look at Fig. (**1.2**), you will see that not all of Earth's population grows at the same rate. How can we achieve this? Would it be a wise thing to do? Well, this is an entirely different discussion...

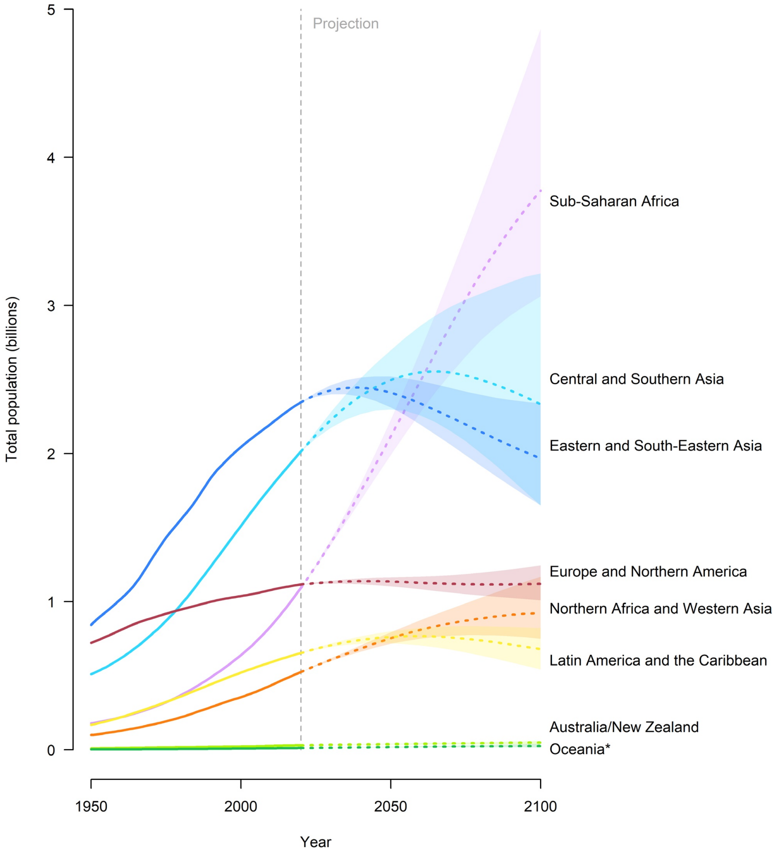

Fig. (1.2). Global population estimated growth, per major regions [1].

There are two ways: the peaceful and the totalitarian.

In the peaceful version, the birthrate steadily decreases due to socio-economic factors. The dissolution of the traditional family, decreasing fertility, raising the cost of living – which, on the one hand, raises the average age for starting a family and, on the other hand, decreases the average children number per couple – the easy access to contraceptive means and abortion, *etc.* All these have led to negative demographic growth in areas like Europe or Japan (even at alarming levels in Romania, for instance!).

The even worse alternative is that some governments enforced active measures to limit their population numbers. The most extreme example is the infamous "one child policy" in the People's Republic of China.

A series of ill-designed policies of the Communist regime led, from 1959 to 1961, to what was probably the worst famine in human history. Over 30 million people perished. So, what conclusions do you think the party drew from this tragedy? No, it was not necessary foreconomic, political or ideological reform. The conclusion was that there were too many Chinese on the planet!

In 1970, the regime started a repressive policy to limit birthrates to a maximum of two children per couple. During that period, it was unusual: other countries, such as India and Bangladesh, used various methods, more or less coercive and inhumane, to enforce two-child policies (including paid or forced sterilizations).

After Mao's death, the new administration of Deng Xiaoping went even further: one child per family, with some specific exceptions. Coercion methods varied from fines, harassment and threats ("extra" children would lose the right to state education and housing *etc.*) to arrest and force abortions/infanticide. A plethora of human rights violations, target both unborn and born human beings.

The consequences of these policies were horrific. Officially, the regime admitted an average of 13 million abortions/year, meaning a total of 336 million (unofficially, there were probably, several billion) [3].

Furthermore, not even born babies escaped! Countless were abandoned or even killed, to avoid reprisals from the regime! An even more dramatic situation for girls, selectively abandoned or aborted, especially in rural areas.

Finally, although, legally, ethnic minorities were somewhat protected, the regime targeted them preferentially. Forced sterilizations are still a reality, aiming today at wiping out the Uyghur people in Nord-West China! [4]

However, no matter if this demographic constriction is a forced one or not, its consequences are similarly negative. First of all, the population is not a water tap whose debit can be easily regulated. Lowering birthrates now will not make elderly generations disappear. They will grow older and older, making the average population age higher and increasing the ratio of retired persons to active ones. A lower global income must be shared to about the same number of pockets. Countries like Romania already feel serious pressure on public social assistance budgets.

Of course, we could increase the retirement age, but this is just a palliative since the problem would continue to worsen. It is improbable that any medical or technological progress could make our fellow citizens work at 90 years of age! And it is not just about money, but resource distribution. Less and less workforce would have to provide food, drinking water, electricity, *etc.*

This also affects the overall development of human society. Just think how interconnected and diversified the contemporary economy is! One thousand years ago, farmers and herders formed the bulk of the world's population, with some small numbers of traders and artisans and an even smaller number of people living on the work of those above (aristocrats, clergy). For comparison, those who participate in the XXIst Century economy, fulfill extremely varied functions, from electrical engineers to lawyers and political analysts to teachers. A huge number of occupational niches require a huge number of people.

Without all these, our society would simply devolve: if we want a Global population like in the 1000s, we should be ready to live like in the 1000s!

Finally, there is one more issue, especially in the totalitarian, *i.e.*, Chinese-style, demographic policies: sex disparities. Basically, if one family needs to choose, it would rather choose a male child. And it is not just a pre-modern mentality, but an objective economic need: a family of farmers will always prefer an offspring capable of the brute physical labour needed to keep the farm going. Also, someone able to support the family when parents are aging; there is no secret that developing societies have significant gender inequities when it comes to average income.

It is sad, but true. At the beginning of Communist China's restrictive one-child policy, the solution was a simple and barbaric one: many couples abandoned their newborn daughters. In the best case, in state-run orphanages; in the worst case, directly in the woods! The same story repeated millions of times in other countries with anti-natalist policies. The modern solution is a more subtle, but no less inhumane one: determining the sex of the unborn and selectively aborting girls.

Even if we ignore the ethical horror, lets see the consequence: more and more boys and less girls. In 2012, in mainland China, the ratio reached 118:100, with some "extra" 40 million male citizens. It is hard to tell how they will be able to find partners and to what tensions this could lead in a nuclear military superpower [5].

Of course, the national issue can be solved through immigration. One could "import" the workforce and even wives (Southeast Asian and North Korean, in China's case). But the issue will become a Global one! Could we bring in extraterrestrial migrants?

And, to make sure I am not the only one alarmed by this problem, in August 2019, at a public conference, Elon Musk said (with the determined approval of Alibaba founder, Jack Ma): "*Most people think we have too many people on the planet,* *but actually, this is an outdated view [...] The biggest issue in twenty years will be population collapse. Not explosion. Collapse.*" [6]

As an update, governments enacting anti-natalist policies were often forced to withdraw them. Since 2015, China's demographic policy shifted to a two-child policy, while in August 2021, a new amendment to the Population and Family Planning Law made the three-child policy official. This means a wide array of mostly financial incentives to counterbalance the dramatic decline in fertility.

While the exact stimuli to be applied and their implementation means are yet to be decided by the Chinese government, some specialists are rather skeptical about the results of these measures. It seems that, just like in more democratic societies, other factors came to affect birth rates, some of which might be dominant today: high costs of living, poor childcare infrastructure, and poor social support systems for the elderly, rather than legal restrictions [7].

During the Post-War era, Japan also experienced a double demographic setback: a decline in the number of children per couple, followed by a decrease in marriage rates altogether. One of the most industrialized nations on Earth, Japan is also one of the most seriously hit by demographic contraction. In 1972, the government launched a scheme of incentives to support families with three or more children below a certain income level. Parental leave regulations were reformed in 1992, while in 1994, a program to build daycare centers for children in the country was launched.

Other developed countries tend to follow similar policies nowadays. Still, results are mixed, and the outcome is rather hard to predict [8].

We can conclude that today's humankind is caught between two equally undesirable perspectives. Population growth would reach the sustainability limits of Earth's environment. We would need more space. Population shrinking or containment is not an option since it leads to economic and societal collapse. If this is the case, more space would still be the solution, by lowering the costs of living resources, like it did in colonial societies of the past centuries.

1.2. Resource Management

If we agree that demographic growth cannot and should not be stopped, let's see the current situation of resources.

There is a wide variety of resources necessary for a post-industrial civilization. Of course, the most important ones are always the same: air, water and food.

Surely, food has the useful feature of (re)producing itself naturally. At this moment, we are probably on the edge of a new agricultural revolution, based on informatization and robotization, vertical agriculture, *etc.* Likewise, it is obvious that sustained population growth will lead, somewhere in the future, to reaching the limits of any kind of agricultural production.

You might say that water and many other resources can be recycled. And you would be right: we can, and we must recycle them.

But, take a look at Fig. (**1.3**).

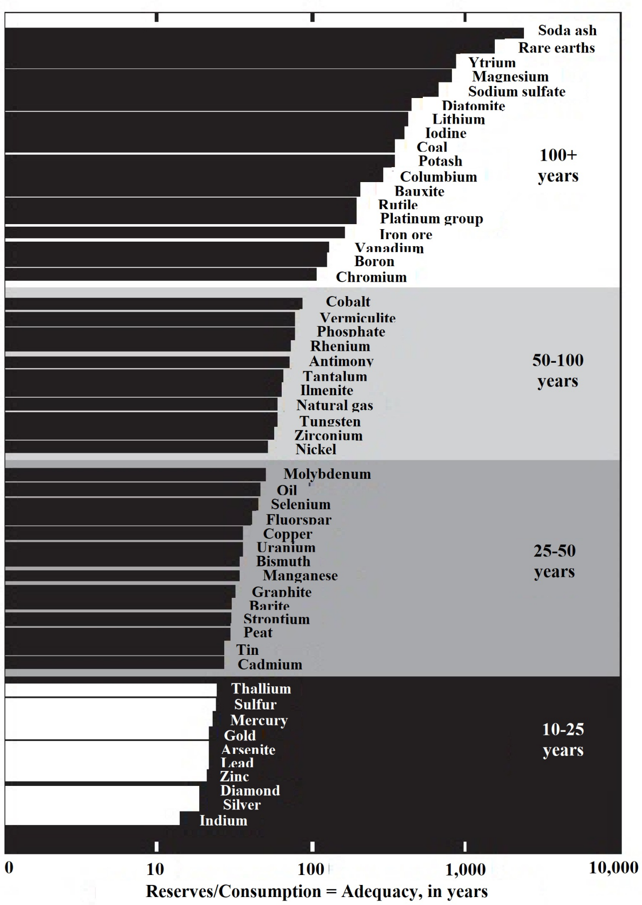

Fig. (1.3). Estimated availability of various mineral resources [9].

Most chemical elements and minerals in this chart will probably sound a bit unfamiliar. Yet, they are essential. Lanthanides, tungsten and indium are important, even crucial to building electric conductors and semiconductors, circuits, diodes and also various metal alloys. Devices that are ubiquitous today, like the laptop which I use for writing this book, the mobile phone from which many fellow citizens are inseparable, photovoltaic panels that bring us clean energy or the LEDs that illuminate our homes, all contain such metals.

And their consumption does not grow only because the human population is growing, but also because our technological level is increasing. Of course, they can be recycled, but demand is continuously rising, and reserves are finite. Even the upcoming agrarian revolution mentioned above or resource recycling processes need technology and, thus, minerals.

As mentioned above, any prognosis is risky. But there is no risk in assuming that any mineral deposit is finite. Or that our planet hosts a limited amount of such deposits. The planet, yes, but not the Universe!...

1.3. Frontier Spirit

There are other reasons why stagnation and perpetual clinging onto this tiny rock called Earth are not an option.

Look at the two graphs in Fig .(**1.4**).

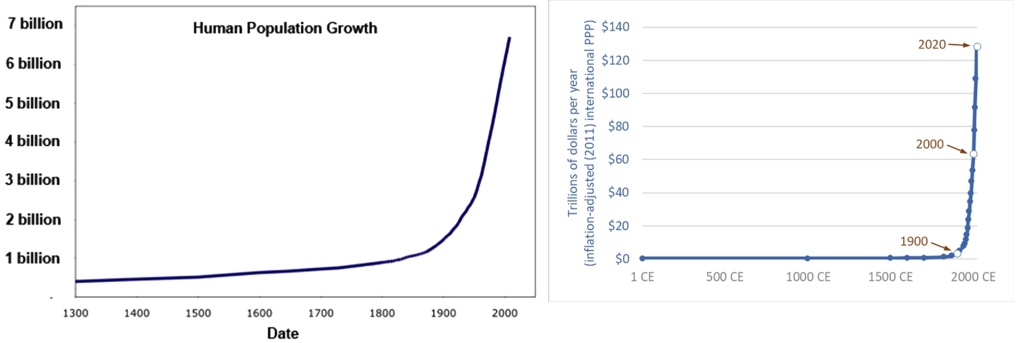

Fig. (1.4). Population growth [10] *versus* economic growth [11].

They basically look the same, don't they? The first curve represents population growth in the last millennium, while the second one is planetary Gross Domestic Product growth. They both show an exponential tendency. In other words, a higher population number/GDP will increase faster. Is there any connection between them?

There surely is! More people produce more. But there is more to it. Imagine a curve representing the technological and scientific level of human society. For hundreds of thousands of years, humankind lived in the Stone Age, with nomad hunter-gatherers barely surviving the next day on local natural resources. Only 12,000 years have passed since we got to master agriculture, have stable communities, and have economic and socio-political diversification. 5,000 years ago, metallurgy became widespread. There are only two centuries of industrial history. And informatics, robotics and space exploration are just progressing in our age. 20 years ago, stem cells, bionic prosthetics or online social networks were merely science-fiction concepts!

And this also determines the overall material development of society. Most earthlings in 1900 (meaning the huge rural population and people in underdeveloped countries) lived in conditions closer to Neolithic ones than those in 2020.

What about politics? Democracy is a relatively old "invention”, but for centuries, it was extremely rare (ancient Athens, merchant republics, Ibadi imamates, "tribal democracies”). A bit more than two centuries ago, the American and French Revolutions really brought it to light. But in 1950, most states on Earth were still dictatorships or colonial subjects. Even in the USA, Civil Rights Acts (officially outlawing any racial discrimination) were only adopted in the ‘60s. Most countries including Romania won their freedom in the ‘80-‘90s.

So, demographic growth, economic and material development, and political progress are all exponential. Why? Simply put, more people mean more ideas, more chances for them to get together (compare current communication means to those in the Middle Ages, when most people – and the ideas they carried – rarely left their native village or town!). But a larger population also creates the need for socio-economic progress. How could a Stone Age economy support over 7 billion people?

So, demographic growth determines and simultaneously requires progress, while progress determines a demographic increase. They are inextricably linked.

What happens when any of these curves flatten? In the European Union, political leaders constantly deplore competition loss compared to the USA or to emerging powers in Asia or Latin America. Some even speak of a general decline of the "West” (whatever they choose to mean by that). We are a declining, aging population that seems to have lost its breath. It even seems that politico-ideological debates are becoming derisory. From often tense quarrels between the Left, Right and Center, including their extreme versions, in the first half of the 20th Century, from grand visions of principles, rights, democracy or nation, we came to “issues” like "gender identity” or "toxic masculinity”! Complacency and decadence...

Do you know which was the time and place with possibly the highest social energy? 19th Century and the first decades of the 20th, in a continuously expanding world, with new territories to discover and new scientific domains to explore. And nowhere was this more pregnant than in the New World.

New lands to settle and administer, offering a sink for Europe's demographic growth and a way to escape its social problems. New forms of government to try. And, obviously, new technical means to "tame" these landmasses. How many inventions were born in that era! Of course, there were also downsides, as many native peoples can testify, but Evil existed in any society.

During the first years after World War II, there was another epoch of optimism, energy and intrepidness, maybe more obvious when looking at the emergent space programs of the 50-70s. Humans reached the Moon... And then... nothing!

This is exactly what contemporary world lacks. A new heroic age, of courage and ingeniuity, to wake us from complacency and give us a new sense. New limits to fight and overcome. A new frontier spirit.

But for all these, we need a frontier. Where to find it on this small and crowded Earth? Nowhere, because it is to be found out there, in the big Universe. It will give us the chance to withstand any imaginable catastrophe and to survive, as a species, forever. It will give us the resources and space needed to thrive. And it will give a breath of fresh air to our society.

Certainly, there are some futurists envisioning another scenario: transhumanism. We could alter our own bodies through genetic engineering and/or cybernetics. Or we could "upload" our minds into robots or, directly, into a supercomputer, to live eternally in an infinite virtual reality [12].

Personally, I am a skeptic when it comes to such solutions. First of all, an upload of human conscience into an informatic device does not mean immortality. Anyone who has ever installed sofware from one device to another knows that what he installed is merely a copy. A computer with my thinking routines would be a remarkable device and would surely outlive me. Yet, it wouldn't be me in that device, but a mental "twin".

Furthermore, is it good, is it wise to change our bodies as we like? Wouldn't we lose our very essence as human beings? After all, the idea of a mobile soul, that is separate from the physical body is not even supported by the Scriptures (at least Monotheist ones). The Book of Genesis (2:7) literally tells us: "*And the Lord God formed man of the dust of the ground, and breathed into his nostrils the breath of* *life; and man BECAME A LIVING SOUL.*" A soul without a body or a body without a soul is barely conceivable!

CONCLUSION

Humankind is heading, slow but steady, towards a major Global crisis. This crisis involves several demographical, economic and socio-political aspects, but it can be easily summarized in one idea: we are running out of living space. Our growth and demands are continuous, while Earth is finite.

Thus, to survive, progress and maintain our essence as a species, we need to learn how to exploit this huge space that the Cosmos offers.

The future of *Homo sapiens* is to become *Homo universalis*.

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CHAPTER 2

Colonizing Earth

If you look the right way, you can see that the whole world is a garden.
Frances Hodgson Burnett

Abstract:

Currently, the human settlement of planet Earth is suboptimal, roughly covering some 15% of its surface. Remediating this problem involves several approaches. Inhospitable land areas can be "greened” by using modern technology, while the efficiency of current settlements can be improved. But humans could also take advantage of such new technologies to colonize the surface of still water bodies, underground and underwater environments. This enterprise would help us learn revolutionary new ways of providing food, light, heat and electricity to human populations, techniques that would also be applicable to other celestial bodies.

Keywords: Deserts, Green architecture, Seasteading, Settlement, Underground cities, Underwater colonies.

No, you do not hallucinate! No, this is not a typewriting error. And no, the author has not gone mad at least, I don’t think so!

Surely, Earth has been our abode, as a species, for over 400,000 years. Fellow human beings live in all its corners. But do we really use it at its full potential?

Look at the image below (Fig. **2.1**).

This is how our planet looks at night. Such images offer a good clue about the global distribution of the human population. Bright areas host large amounts of people, with the most illuminated spots being urban centers. But we can also see almost dark areas. These regions are sparsely populated (or North Korea, for entirely different reasons).

Dan Răzvan Popoviciu
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Fig. (2.1). One of the many images NASA offers to the public shows a night view of planet Earth [1].

Actually, of the entire Earth's surface, 71% are water bodies (oceans, seas, lakes *etc.*). Of the landmass surface, half is represented by rather hostile environments: extremely dry areas (deserts, semi-deserts, arid steppes), ice masses and tundras, mountain ranges and high, dry plateaus (Tibet, for instance), swamps and other wetlands, rainforests and dense boreal forests in cold regions of the world.

Simplifying all this, we could say that humankind piles up on around 15% of the planet's surface. What is to be done?

2.1. SETTLING LANDMASSES

Let's take, for instance, deserts – some of the most inhospitable and sparsely populated places on Earth. Environments continuously expand due to deforestation, intensive agriculture, overgrazing and climate changes.

Of course, there are many plans (some already under implementation) to halt this expansion, by creating forest barriers. Planting vast areas in Niger with *Faidherbia albida* (a tree similar to acacia) during the final decades of the last century already led to "re-greening" some 3 million hectares. Over a quarter of a million hectares were returned to agriculture. That means food, economic production and the possibility to populate regions that, in the 70s, were effectively turned into wastelands. For instance, the cereal production in these areas (millet, sorghum) increased by 20-85%, and horticultural production even quadrupled in some cases! And all these by "simply" replanting some trees [2]!

Can we do more? Of course! Especially in regions with natural water resources. One of the most grandiose such projects is the New Valley Project or, shorter, the Toshka Project.

Egypt is one of the countries most affected by the contradiction between sustained demographic growth and low habitable surface. Around 100 million citizens are forced to "crowd" on the narrow Nile Valley and in some other small and relatively wet areas (about 5% of the country!). The rest being, obviously, desert.

In 1997, the Egyptian government conceived a simple project with major consequences. In the southern part of the country lies Lake Nasser (a man-made reservoir created on the Nile). To the west, a rise in groundwater levels, due to water accumulation in Lake Nasser, created a row of new lakes, called Toshka Lakes (Fig. **2.2**). The idea is to drain their water, through irrigation canals, to the north, with the terminus point around Baris Oasis. The final purpose is to expand the country's arable land by 40%, returning to public use vast areas west of the Nile, in the Southern Desert [3].

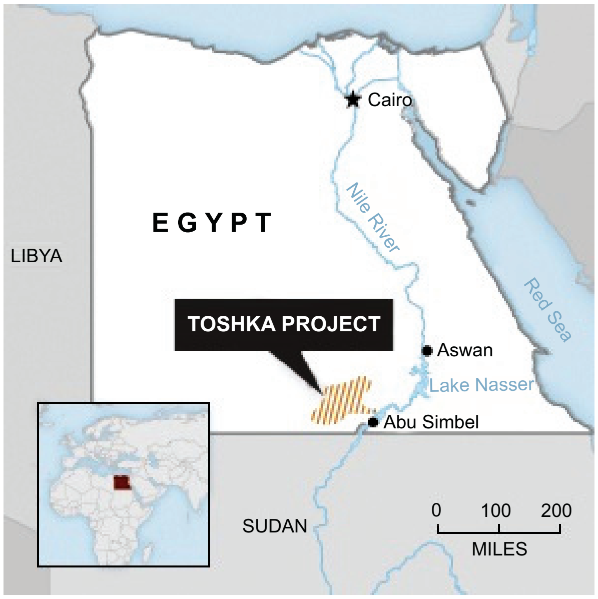


Fig. (2.2). The area to be irrigated and returned to agriculture through the Toshka Project [4].

The Toshka Project is just a small part of an array of grandiose plans, with an estimated cost of 70 billion dollars, aiming at creating over 17,000 km^2 of arable land in the desert. Unfortunately, local political evolutions temporarily halted these plans – just 80% of the 310 km-long Toshka-Baris canal (the main feature of the project) was completed. Recently, however, the new regime led by General al-Sisi expressed its wish to resume work as soon as possible [3].

Not only the Southern Desert is targeted, but also other regions of Egypt. For example, using man-made canals and pumping stations, authorities managed to expand arable lands west of the Nile Delta, in the Beheira Governorate [5].

Surely, there are potential drawbacks to this concept. There are some concerns that salts present in desert soil might make the water too saline and unsuitable for irrigation and could also affect groundwater. Furthermore, over usage of Nile water could cause a hydric deficit in other regions and political tensions with neighboring countries (Sudan, Ethiopia).

More good news is received from China. Most of its Western regions are deserts, semi-deserts and arid highlands. Even more, decades of intensive agriculture and systematic deforestation, all on a background of erosion-prone soils, led to an expansion of loess deserts in Central and Northern areas.

Since 1998, the regime in Beijing launched the *Xibu Da Kaifa* (Open up the West) initiative, a set of large-scale reforestations, for halting and resettling deserts. The goal would be to "re-green" a total of 17.33 million hectares of arid land (plus re-naturalizing 14.67 million hectares of unsustainable agricultural land). Results are certainly, mixed ones, and the idea also has a rather worrisome political substrate systematic colonization of some regions, against and by marginalizing native ethnic groups: Mongols, Uyghurs, Tibetans), but such measures are a good example of how regenerating natural ecosystems (forests, steppes) can go alongside with expanding arable lands, in a struggle to tame the desert [6].

This struggle requires an ingenious use of novel technologies. For instance, authorities intend to use solar energy to desalinate water, installations that would help condense atmospheric water, new biochemical solutions (a plant extract used to enhance soil cohesion and water retention between soil grains) and new agriculture, one that should be more effective in using available space (in order to limit arable land expansion on behalf of natural vegetation). All these to create some 13,000 hectares of new arable land in Inner Mongolia, in just a few years! 70 agricultural species would be grown, many of which are native or acclimatized to the region. Basically, a terraformation of the desert [7]!

Qatar and Jordan are two other countries that use integrated approaches to recover arid regions. In collaboration with fertilizer-producing companies, NGOs and innovative architects, Qatar opened an experimental center that includes concentrator photovoltaic installations and greenhouses that are cooled with salt water. Electricity produced by the photovoltaic power plant is used to evaporate water, thus cooling the greenhouses – a major problem in an arid tropical climate – and, through water condensation, to irrigate crops. But this is just a pilot experiment, part of the *Sahara Forest Project*, a major, non-governmental campaign to reconquer the deserts, with subsidiary projects in various states of the Middle East and the Mediterranean Basin [8].

All these projects are in the course of implementation, but there are others, at even larger scales, that have not yet passed the concept phase. The main limiting factor is water, an issue with two possible solutions.

The first consists of transporting this vital liquid from areas that benefit from a natural excedent. This is the case for the grandiose "*Water for Life*" initiative. The water source should be Norway – a mountain-covered country with numerous freshwater sources, many of them flowing towards the North Sea, after a short passage across local highlands. While some of them fuel the powerful Norwegian hydroelectric industry, a substantial water amount is simply lost to the Planetary Ocean.

Therefore, proponents of this initiative envision draining all this freshwater, by gravitational flow and active pumping, through a 12 m thick magistral pipeline, across Europe, below Gibraltar and into the Sahara, to irrigate a huge region, stretching from Morocco to Saudi Arabia. This water would be used in aquaponic farming complexes (farms that produce both vegetables and fish; there would be over 400 such farms, with a total area of over 1,000 hectares), producing more than 20 million tons of food daily [9].

There is also a somewhat lower-scale and more "classical" equivalent to this: NAWAPA *North American Water and Power Alliance*. First ideated in 1964, but never implemented mostly, due to political and financial reasons, this program involves building a series of pipelines and open canals for transferring freshwater excedents from Alaska, Yukon and British Columbia (areas with geographic and hydrographic features similar to those in Norway), to the prairies and semi-arid and arid areas in Central and South-Western United States, Central Canada and Northern Mexico (there is also a similar project called GRAND – taking water from the Great Lakes). This project would completely reshape the economic geography of North America, offering cheap hydroelectric energy, irrigation and internal naval transportation means to a huge region (Fig. **2.3**) [11].

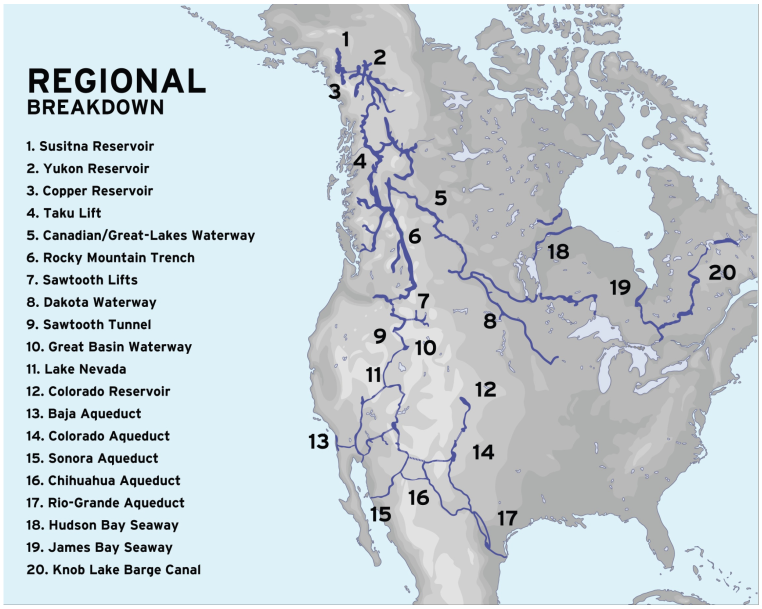


Fig. (2.3). A revised version of the NAWAPA project [10].

There is, however, a much richer water source for irrigation: the Planetary Ocean. And current technology allows the desalination of huge amounts of water.

Here is, for example, a simulation of the reforestation of vast areas of the Sahara and Australia, mainly with eucalypt trees. The main concern of the authors, in this case, was sequestering large amounts of carbon in order to lower or neutralize the anthropic greenhouse effect (which would involve sequestering 7.2-8.8 gigatonnes). The water volume needed would be around 4.9×10^{12} m^3 per year, for the Sahara. There are some major groundwater resources, among which the Nubian Aquifer, but those would be depleted in a few decades.

However, the main idea is that of a geophysical feedback. The mathematical model employed by the authors indicates, for the Sahara, a 20-fold increase in rainfall volumes due to reforestation (700-1,200 mm/year). In just 20 years, this would lower the water amount necessary for irrigation by 40% (from 500 to 300 mm/year). The same would also function for Australia.

Reverse osmosis desalination technology decreases irrigation costs, up to 0.53 USD per m^3 of resulting freshwater, plus pumping and transport costs. A network of desalination plants (powered by nuclear, wind or solar energy) would provide the necessary water in an ecologically "clean" manner. Surely, there are other issues, such as nitrogen deficit in desert soils – easy to fix by planting *Acacia* trees or other nitrogen-fixing species legume-bearing plants have root nodules hosting endosymbiotic bacteria that convert dinitrogen to organic nitrogen. Such reforestation would allow a profound alteration of the local climate and an expansion of agricultural crops and living space [12].

Such an enterprise would indeed be expensive. A private company, Y Combinator, calculated an estimated overall cost of “re-greening” the Sahara: 50 trillion dollars [13]! Of course, that is huge, but it is just twice the current public debt of the United States, for instance, while the economic and politico-demographic benefits of such a program would be enormous.

One of the most innovative ideas in this field involves concentrator photovoltaic cells. Briefly, light is concentrated, using mirrors, onto a cell containing molten salt as a heat transfer fluid. Heat is then transferred to water, which, turned to vapor, activates a turbine. But water vapor is a resource that could be used for desalinating; through evaporation, water is pumped from the sea/ocean/salt lakes (Fig. **2.4**).

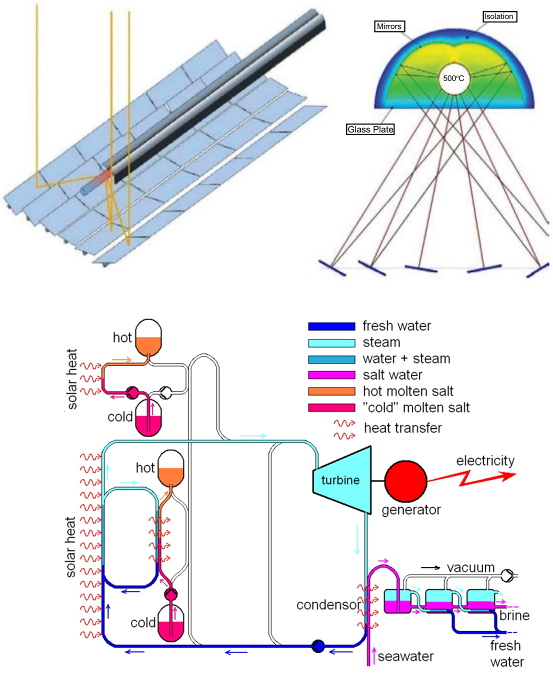


Fig. (2.4). Concentrator photovoltaic cells – most likely the key to "greening” deserts [14].

More recently, photovoltaic cells with incorporated micro-pipes allow the miniaturization of the whole process. The technology is extremely suitable for areas with strong insolation and high temperatures, which is why many countries in such regions have already built or are going to build pilot plants: Cyprus, Egypt, and Australia [14].

As for the cold regions of Earth, it seems that they are already greening, due to contemporary climate changes. Not as fast as we could expect, but lower and wetter areas in the Arctic tend to develop much more abundant vegetation [15]. The ice melting and opening new transportation routes could lead to massive colonization of the Far North (and, maybe, the Far South). Of course, we should always consider the negative effects of this "meltdown" on the Global climate.

Further help could come from orbital mirrors. Satellites bearing extensible sails covered with reflective materials (MgF_2, SiO_2, a mixture of indium and stanium oxides), on geostationary orbits or not, could lighten the sky during the long polar nights or short winter days at higher latitudes.

In 1999, the Russian Space Agency placed in orbit such a mirror, 25 m in diameter ("*Znamya 2.5*"), illuminating an area 7 km in diameter. For ground observers, it had a luminosity five times higher than the full Moon (but at a smaller diameter; basically, like a very bright star). Unfortunately, it had a short life: a malfunction led to an almost immediate crash of the device.

To create a pleasant illumination of circumpolar regions, 15-30 km^2 mirrors (or clusters of smaller, below 0.1 km^2 ones) would be enough. However, to provide constant light, similar to that of the Sun, for agricultural and even photovoltaic purposes, a total surface of 2,500-7,500 km^2 would be necessary (clusters of 5-10 km^2 reflectors) [16]. This is not easy to accomplish, but neither impossible, especially because this technology will prove useful in other situations, as you will find out in the chapter dedicated to Mars.

However, efficient landmass settlement does not just imply irrigating, greening and colonizing hostile environments and more efficient usage of already available living space.

Take a look outside your home. What do you see? Very likely, blocks of flats next to other blocks of flats, or houses next to houses, with a little bit of green space beside them, a park here and there. And, if you live in a neighborhood of houses, some have gardens where their owners might grow some vegetables.

But, if you want to see agricultural production, you will have to get out of your town or village. The same if you wish to see a forest, a pasture or any other kind of natural ecosystem.

Thus, in contemporary society, there is a clear distinction between anthropic ecosystems housing, administrative and industrial spaces, agroecosystems and natural ecosystems. Each has its own, separate place. And this isn't right! This way, landmass usage is not efficient, and these three ecosystem types will compete with each other.

One of the most puzzling things I have ever seen in my life is the massive territorial expansion of my home city. New neighborhoods of houses and blocks, or huge commercial complexes continue showing up in places that not long time ago were crop fields, littoral sandspits, wetlands, pastures or, simply, ruderal ecosystems (the fancy, scientific name of abandoned fields). The same goes for the entire country, although the Romanian population is constantly declining! In other regions, agricultural terrain and pastures are expanding, on behalf of natural areas. The latter are the ones affected in all situations, being constantly reduced throughout the world.

What needs to be done? It's obvious: integrating these main three types of ecosystems in the same space. A town/village that would simultaneously host human inhabitants produces a large part of its necessary food and has a high percentage of green areas.

In 1959, typhoon Vera devastated several towns in Aichi Prefecture, Japan. The next year, the (then) young architect Kisho Kurokawa – one of the founders of the Metabolist Movement, ideating organic urban growth – proposed the concept of an "Agricultural City". Formed of 500×500 m housing complexes, each hosting 200 people, this town would have been completely suspended and alternated with crop fields (Fig. **2.5**). All houses are suspended on pillars, and road infrastructure is located 4 m above ground [17].

Yet, the idea of agro-urban symbiosis was rather marginal until now, at the beginning of the 21st Century, when cities grow, and their food demand also increases. Estimates show that, around the half of this century, 80% of the total agricultural consumption will be due to urban settlements. This implies a growing dependence on rural regions and high food shipment costs (that are translated to environmental costs: growing greenhouse gas emissions). But it also means a growing need to get out of the so-called "gray infrastructure": the typical, concrete-covered, polluted city [18].

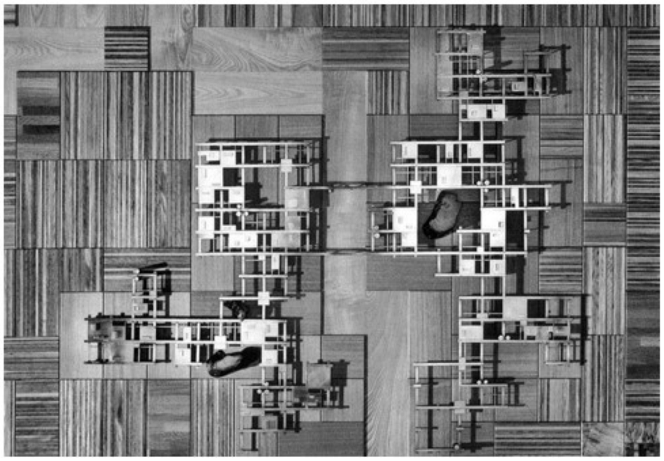


Fig. (2.5). The “Agricultural City” imagined by K. Kurokawa, seen from above [19].

There are many ideas, from personal gardens on balconies and roofs to communal gardens and greenhouses. The final target is real farms fully integrated into urban landscapes-agricultural production spots and a source of ecological services for a growing urban population.

Green façades, rooftop farms on commercial centers or blocks of flats with integrated mini-farms see Fig. **2.6**.

Fig. (2.6). The Farmhouse, a block of flats with mini-farms, imagined by Fei and Chris Precht [20].

The most efficient is vertical farming: real vegetable "factories”, with a controlled internal environment, hydro-/aeroponic culturing, on multiple levels, with the possibility of recycling waste (through composting, for instance) [18].

On the other hand, neither integrating natural ecosystems in future cities is impossible and not even expensive. After all, there is a long history behind it, starting with the Hanging Gardens of Babylon. The problem here is urban planning: many contemporary metropolises were simply not designed to host large enough green spaces, and now any such change would be too expensive.

Yet, in the future, this will be a key issue in designing new neighborhoods or cities. A “green” city is not just less polluted, but also healthier for its residents (due to the effect of volatile essential plant oils, featuring antimicrobial properties, and the relaxing effect on human psychic). Thus, it is also more productive economically [21]!

Furthermore, such urban ecosystems ensure temperature regulation and a pleasant climate, especially in the hottest periods of the year, filter from 70% (trees planted next to roads) to 85% (parks) of the polluting solid particles in the air, lower, with up to 50%, noise pollution, stabilize soil and drain excess rainwater and, last but not least, can host impressive biodiversity [22].

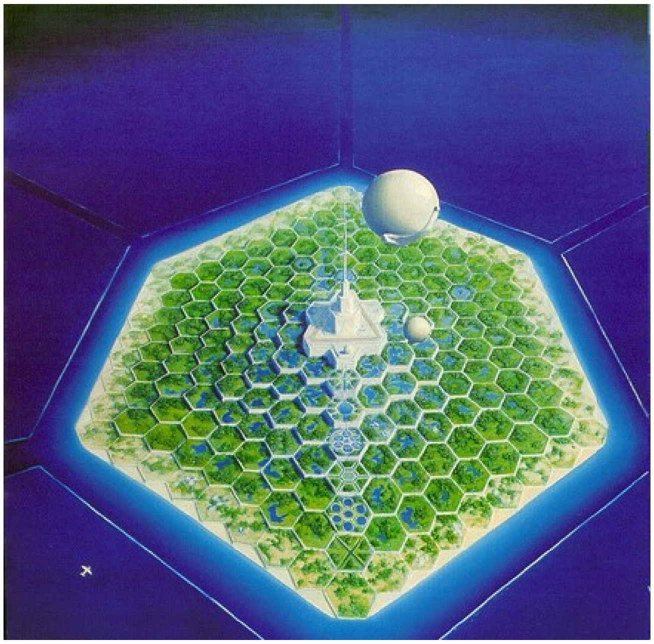


Fig. (2.7). Aquarius, an example of integrated agro-urban settelement [23].

There is an architectural design that allows an optimal combination of all three ecosystem types. Made popular by Marshall T. Savage, it is the main idea behind Project Aquarius: floating urban colonies (for more, see Subchapter **2.3**). The concept can also be applied to land settlements.

It is the so-called *tectonic architecture*: structures that mimic natural landforms. In this case, hexagonal housing modules (the easiest shape to combine in complex megastructures) would be organized on several levels, the final result having the shape of an artificial, terraced hill (Fig. **2.7**).

Residential spaces would consist of these modules (especially outer ones). Central modules would contain utility spaces (transportation networks, industrial and commercial centers *etc.*), illuminated by sunlight – directed through reflecting tubes or fiberglass – or using electricity (or mixed systems). The compact shaping of living areas in such megastructures would reduce internal distances and make transportation easier.

But, most importantly, the outer and upper surfaces of the modules would provide space for farms, micro farm complexes or natural vegetation. Imagine a huge “ant mound” populated by thousands of people, covered by farms, pastures, parks or even forests, that can expand "organically” by adding more hexagonal modules [24]!

2.2. DEEP BELOW

One of our most common mistakes is considering our planet as a two-dimensional space. We open an atlas, look at flat maps and see how cities, provinces and states lie on this surface, and maybe we ask ourselves if there is more to settle.

But our world is three-dimensional! and this means that Earth is round or its surface has various landforms. But there is also a vast underground environment and an equally vast atmosphere. We can search for new territories right below our feet or above our heads!

Can we really do this? Even since the Paleolithic era, humans have chosen caves among other possible shelters. Then, as technology and workforce allowed, they began digging their own underground structures. One of the oldest and still surviving such structures, dating from the Bronze Age (cca. 3000 BC) – is the Terelek tunnel, below Kızılırmak River, in northern Turkey! The ability to dig tunnels and underground canals became more evident 2700 years ago, in Persia, when people dug the *qanat* – extended water transport networks, for human consumption and irrigation [25].

However, such digs were not limited to tunnels. Even since around 4500 BC, partially or totally underground villages (built this way due to climate and security reasons) were common in Judea and surrounding regions [26]. But the largest and most widely-known such settlements are those in the Cappadocian Plateau (nowadays in Central Turkey). Initially dug by the Phrygians (8-7 centuries BC), expanded during the Byzantine Empire and used up to the beginning of the 20th Century, each of these temporary or semi-permanent settlements was able to host, tens of thousands of people during wars. Nine such towns are currently known, dug in the soft volcanic tuff of the region (Derinkuyu, Kaymaklı and Özkonak being among the largest; (Fig. **2.8**), with up to 10 levels each, reaching depths of 40-60 m. The settlements include houses, warehouses, stables, churches, water and ventilation wells and also connective tunnels between them, up to 8 km in length [27]!

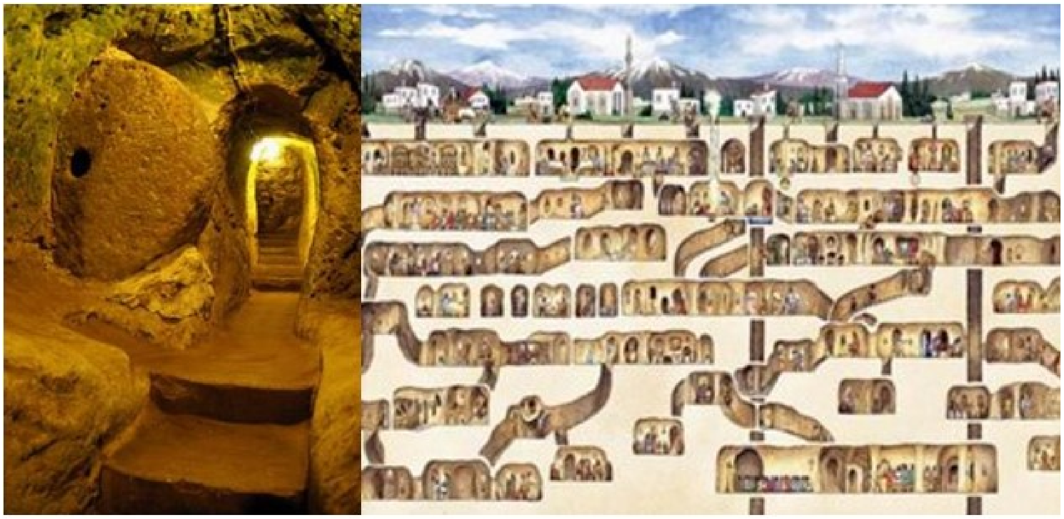


Fig. (2.8). Malakopi/Derinkuyu ancient underground city (Turkey) [28].

Of course, this trend towards settling subterranean spaces still continues up to these days. And this is because they offer some advantages. First of all, available space: such a settlement can easily extend on multiple levels. Such spaces also provide a constant ambient temperature throughout the year, lowering heating and cooling costs. There is easy access to underground water and geothermal resources, allowing the use of heat pumps, or even thermal springs for heating (Fig. **2.9**).

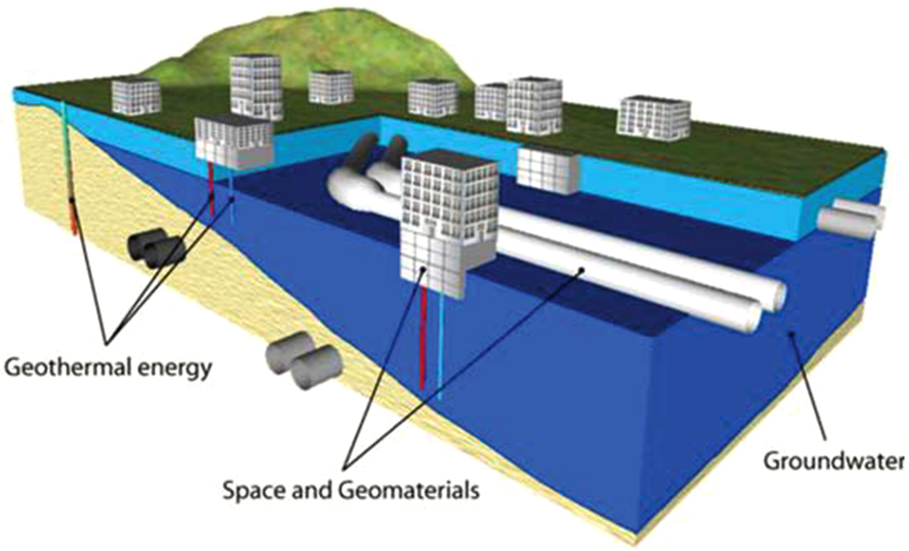


Fig. (2.9). Resources available to an underground settlement [29].

Obviously, there are some drawbacks. Although modern excavation means can be very efficient, digging such spaces requires time and resources. The requirements are certainly lower if the substrate is composed of softer rocks, such as limestone or tuff. There is also the need for constantly ventilating the internal atmosphere. Finally, there is the problem of illumination.

Fortunately, there are several modern solutions to this problem, other than the traditional, energy-consuming electric lighting, even if based on LED technology. Direct illumination implies transporting and distributing natural sunlight. It can also be used in mixed systems, which distribute light from a small artificial light source.

It all starts with light collectors – mobile parabolic mirrors (with adequate electronic control, collectors can follow the Sun's position in the sky, just like a sunflower does!) that focus the light on mirrors that, in turn, transmit it further away. There are also variate light transmission means, including rigid reflecting tubes, flexible reflecting cables and even fiberglass conductors. Finally, terminal reflectors distribute light, just as traditional electrical ones do (Fig. **2.10**).

Efficiency can surpass 50% (up to 65% of the incident light, depending on network conformation). Definitely much higher than if a photovoltaic light transformation to electricity and *vice versa* was used! And the best part is that all this technology is available and already in use [30, 31].

An efficient illumination is also the key to providing food to the settlements, because vertical agriculture aquaponic, hydroponic or aeroponic and unconventional farming (mushrooms, insects) is a prerequisites to colonizing the depths of our planet.

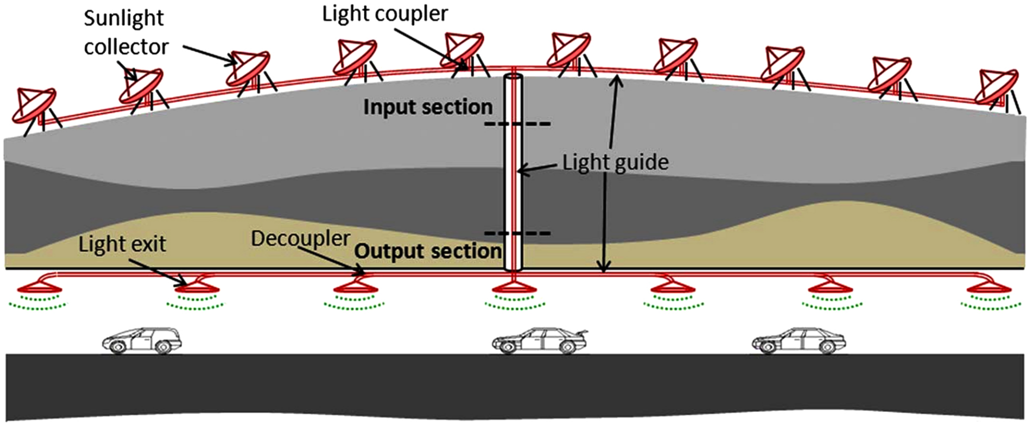


Fig. (2.10). Direct lighting systems for underground spaces [30].

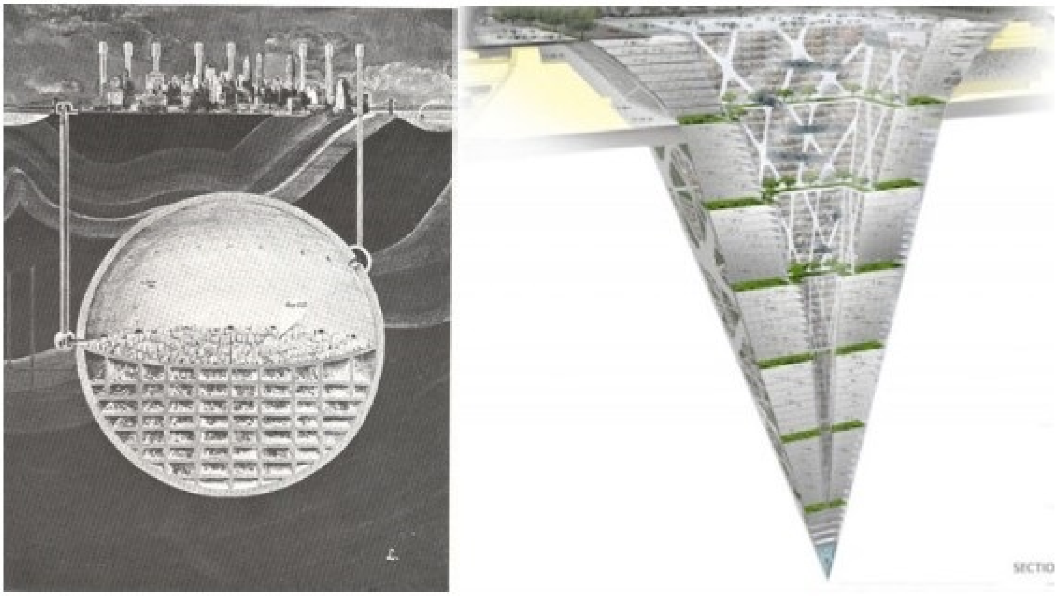
Finally, the technique can be supported by transparent ceilings or rational placement of built structures, especially in the case of semi-open underground cities (built-in disaffected surface mines or other open cavities, with or without a transparent ceiling). If blocks of flats have different heights (preferably decreasing towards the center), this allows natural sunlight to penetrate deeper and reach more housing units. An idea that, while often ignored, should also be applied to surface cities [32]!

Currently, numerous cities are expanding or are planning to expand towards the subterranean environment. Sometimes shy, reusing disaffected underground railway tunnels. In other cases, in a massive and systematic manner. Taking advantage of its favourable geologic context, the Finnish capital, Helsinki, grows deeper and deeper each year. Parking lots, storage facilities, road tunnels and pedestrian tunnels, running tracks, swimming pools, but also the wonderful semi-buried Temppeliaukio Lutheran church (opened in 1969!), not to mention a plan to connect the city with the Estonian capital, Talinn, through an underwater tunnel [33, 34].

Probably, the most spectacular example is Montreal. Even since 1966, local authorities decided to build a vast network of multifunctional underground spaces: for transit, commerce and leisure. An undoubtedly pleasant place for walking and shopping during the harsh Canadian winter (Fig. **2.11**) [35]!

Fig. (2.11). Underground public spaces in Helsinki [34] and Montreal [36].

But we can do more! There are projects for new, completely underground cities. And it is not really a new idea! In 1969, Oscar Newman proposed building an "Underground Manhattan", a network of housing units and roads filling a spherical cavity, 2 km in diameter, below New York City (Fig. **2.12**).



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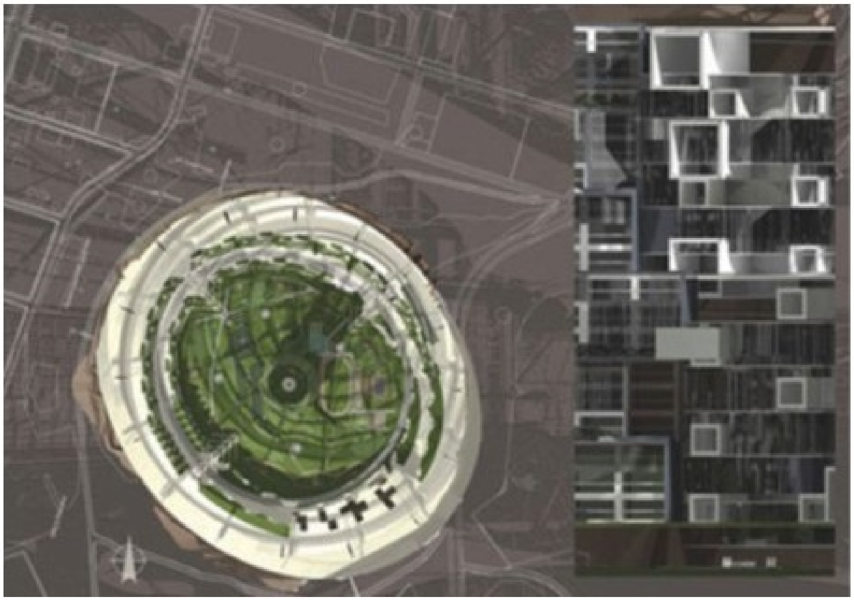

Fig. (2.12). Projected underground cities: Underground Manhattan, Earthscraper, Siberian Underground City [32].

While this was a “brute” proposal, a consequence of the Cold War and of the nuclear threat, the *Siberian Underground City* (projected by AB Ellis), would offer a much more pleasant urban landscape. This city would be built in the former Mir diamond mine, in the Sakha Republic (disaffected, as a surface mine, since 2001). The mine is basically a huge excavation funnel of 1,200 m in diameter and over 500 m depth. This would be covered by a transparent dome, provided with photovoltaic panels, and vertical farms and host 100.000 inhabitants, in open and semi-open residential complexes, with vast parks. This is the advantage of semi-buried cities: they allow using natural sunlight!

Another modern idea is the *Earthscraper*, projected by BNKR Arquitectura (2009), a complex that would be located in Mexico City. A reversed pyramid, 35 stories deep, also hosting around 100.000 inhabitants, plus gardens, offices and commercial complexes, all surrounding a central depression with transparent ceilings (Fig. **2.12**) [32].

Such buildings come with multiple and variate problems. Besides food and light, another issue is transportation. But solutions are also multiple: using underground railways, disaffected railway tunnels, and pedestrian subways. Fortunately, such settlements tend to be rather compact, with short distances to travel.

And there are also solutions for longer distances. Underground automated transport is a concept o the verge of being applied: Cargo Sous Terrain company is planning to create, within the next few years, a network of tunnels covering the Swiss territory that would enable completely automated freighters to circulate [37]! Another idea is to update traditional transportation means by using pneumatic tubes or magnetic levitation (MagLev) railways.

As for thermal needs, estimates show that an underground house should consume up to 60% less energy for heating and 20% less energy for cooling than one aboveground. Thus, settlement expansion towards the subterranean realm would also be eco-friendly [38]! And another great thing: technologies employed would also prove useful in the initial stages of colonizing hostile planets (Mars, the Moon). Or the other way around...

2.3. WALKING ON WATER

If we agree that we can also live on and beneath Earth's continents, there is another environment that we make little use of. 71% of the planet's surface is covered by water: the Planetary Ocean, but also various lakes, lagoons *etc.* For the moment, we are still not very familiar with these environments, at least with their deep parts. This does not prevent us from polluting them or overexploiting their biological resources.

However, if we think a bit, Earth's bodies of water are a huge resource, one that we can benefit from for millennia, as long as we do it in a durable manner! And the aquatic environment could also become a living environment, even earlier than we might expect.

In countries like the Netherlands, reclaiming new landmasses (polders) is already a tradition and numerous port cities, suffering from territorial limitations, begin expanding onto the sea surface. If climate change continues and sea levels keep rising, settling water bodies could become a necessity (Fig. **2.13**). Furthermore, terraforming some celestial bodies, such as Venus or the Jovian moons, might end up creating huge oceans (see dedicated chapters).

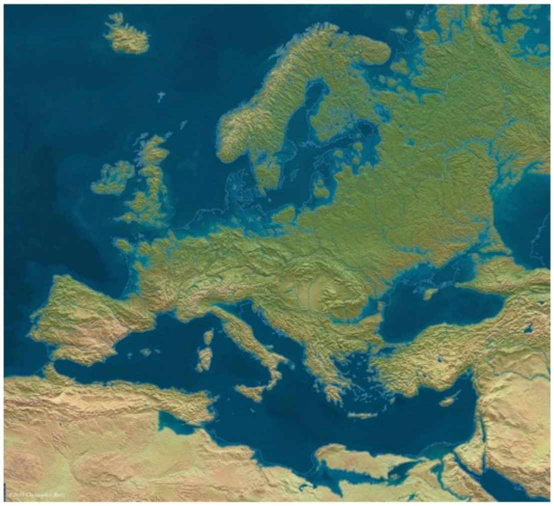

Fig. (2.13). A projected post-apocalyptic Europe: all the planet's ice sheets have melted [39].

Basically, Earth's water bodies can offer two types of environments for colonization. First, there is water surface, through polders or floating settlements. Second, there are the shallow bottoms of lakes, inland seas or continental shelves, places that are suitable for submerged settlements.

Floating settlements are not necessarily a new concept. Many civilizations, such as the Chinese or Aztecs (with their *chinampas*), built floating gardens – an early form of aquaculture. There were also permanent floating settlements. It is the case with artificial totora (a sedge species) islands of the Uros people, in Peru and Bolivia, but also of the marine seminomadic communities in Southeast Asia (*orang laut* – "sea people": Sama, Bajau, Moken and other Malay ethnic subgroups, living all their lives on boats, boat assemblages and stilt houses) [40].

However, it's time to move things forward! Optimal settlement areas are, obviously, lake systems (including the largest ones, such as the Caspian Sea, Aral Sea or the Great Lakes), enclosed lagoons within tropical atolls, shallow seas, protected inland seas (such as the Seto Sea, between the three southern islands of the Japanese Archipelago), but also open sea areas less subjected to destructive weather phenomena.

It is the case with the Intertropical Convergence Zone (shortly, "doldrums"), an area close to the Equator where winds (and, thus, waves) are barely present. There are also other ocean areas where winds are present and storms are possible, but destructive tropical cyclones are not active (Fig. **2.14**).

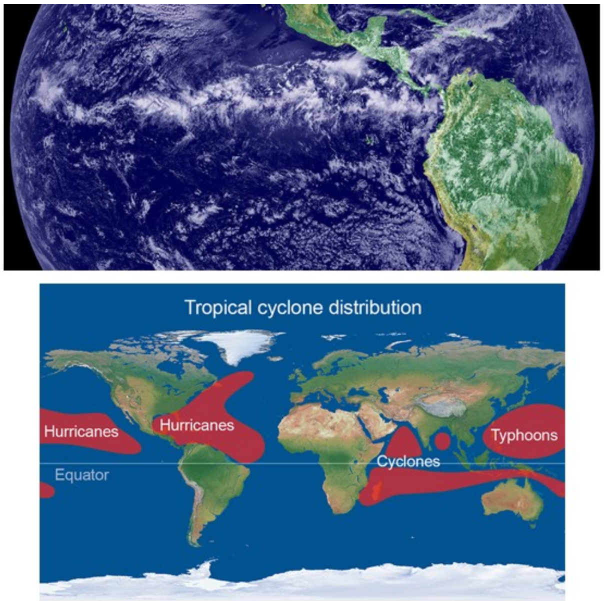

Fig. (2.14). The doldrums [41] and tropical cyclone distribution [43].

There are numerous such projects, implemented or in the course of implementation. Let's start with small-scale ideas! The idea of living on the sea (*seasteading*) is already a reality in many cities of the world – in Amsterdam, for instance. In its most basic form, it implies individual houses or housing complexes located on barges. And not only homes can float! Here is, for example, *The Science Barge*, an experimental urban hydroponic farm powered only by sun, wind and biofuels, anchored in New York harbor (Fig. **2.15**).

Fish farms, photovoltaic power plants, bridges and tunnels, airports, hotels and restaurants, docks, fuel tanks, port terminals and other such structures are being built throughout the world (Fig. **2.15**) [43].

Such structures can be built using one of the cheapest and most widespread building materials: garbage! More precisely, plastic waste pollutes world's waters. The former "Recycled Island" foundation, currently "Clean Rivers", a Dutch NGO, has already started collecting this kind of waste and building floating structures. From the garbage collected in one year, in the Maas river, they built a 140 m^2 floating park in Rotterdam [45].

And there is another cheap material: ice. In 1942, inventor Geoffrey Pyke proposed that the British Royal Navy build several huge "aircraft carriers", in order to take control of the North Atlantic from German U-boats. Each should have been over 600 m-long and 90 m-wide (the prototype was supposed to be 30 m-long, then reduced to 18 m, but it never went further). The building material (actually invented by Max Perutz) was a revolutionary one: *pykrete* or *pykolite*, a mixture of 86% water and 14% sawdust/wood pulp, all frozen and kept in this state.

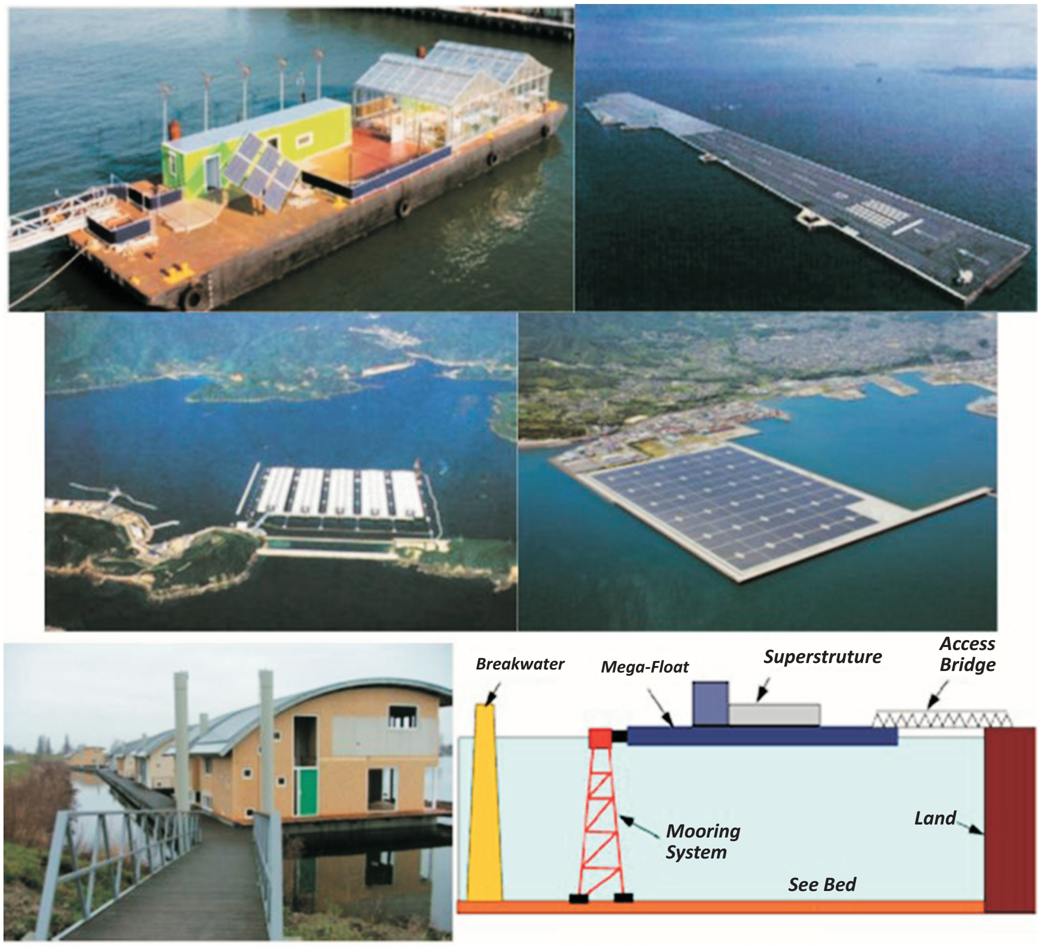

Fig. (2.15). Floating megastructures: Science Barge (New York), airport (Tokyo), oil storage facility (Kamigoto) [43], solar power plant (Kagoshima), housing complex (Maasbommel, Netherlands), the general design of such structures [43].

Compared to the cheapest alternative – porous steel structures, costing \$100-200/m^2 for a functional floating platform – of course, there are some limits to the material's resistance and cooling. When exposed to temperatures above -15°C, pykrete loses strength, so it must be continuously insulated and cooled, especially in warmer climates [46].

Neither traditional materials are to be ignored, especially for building mobile floating structures. *Freedom Ship* (designed in the '90s by Norman Nixon) was going to be an enormous residential complex built on barges, with a total length of 1,800 m, 18,000 housing units, 10,000 hotel rooms, 3,000 commercial facilities *etc.*, hosting a total of 80,000 inhabitants (Fig. **2.16**). The issue with this project costs, estimated to be over $10 billion, this being a luxury floating community. However, these costs can be lowered by using alternative materials [47].

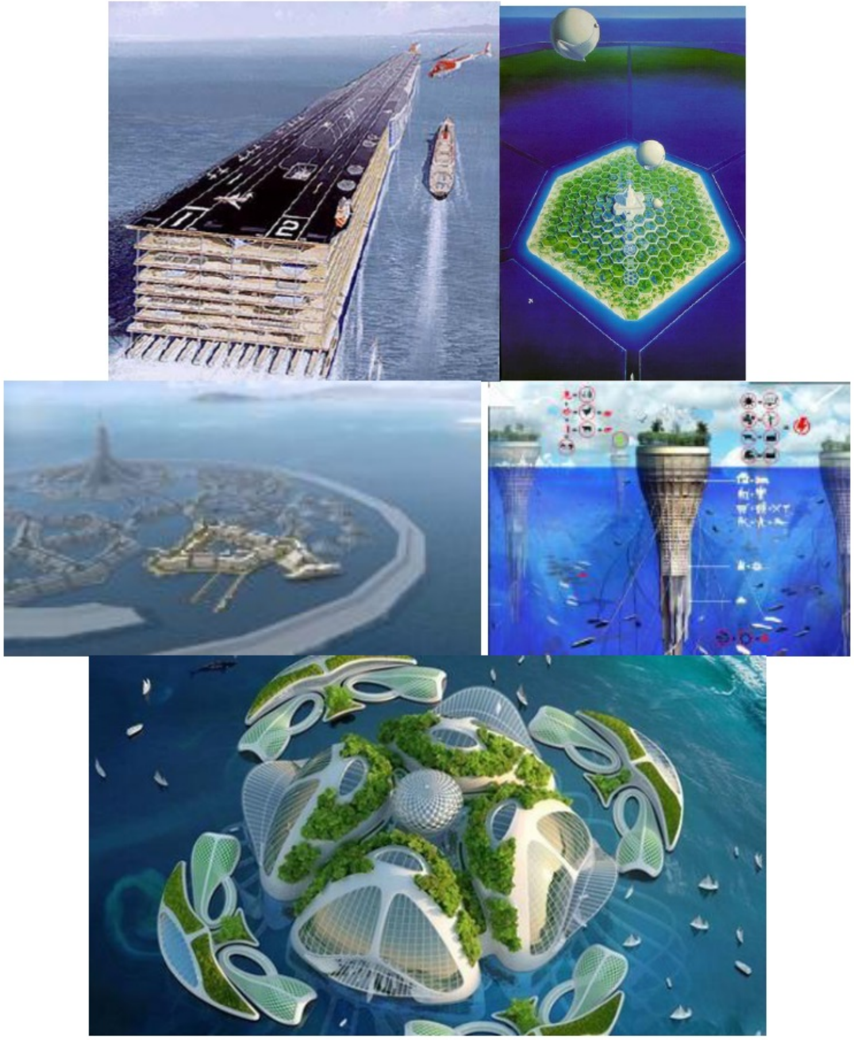

Fig. (2.16). Floating city projects: Aquarius [23], Freedom Ship [46], Floating Island, Aequorea [53], Water-Scraper [54].

A larger-scale project, currently in an advanced stage of implementation, is *5 Lagoons*. Developed by Dutch Docklands, a company specialized in large-scale floating structures [48], in collaboration with the government of the Republic of Maldives, it consists of creating artificial islands in the Maldivian Archipelago. Driven by the favourable marine terrain (atolls) and the constant threat of rising sea levels, the concept includes, in its first phase, building a floating housing complex, with an area of around 740.000 m^2. With villas, golf courses, a hotel and a conference center, a quay and a submarine tunnel (Fig. **2.16**), this pilot settlement, close to the capital Malé, would be mostly a tourist resort, but other such structures, with other purposes, could multiply within the Archipelago [49].

The Seasteading Institute, a non-profit entity having as its declared goal colonizing the oceans, is the author of *The Floating Island Project: French Polynesia*. Similar to the above-mentioned project, it would be located in Fench Polynesia, but for the moment, it is blocked due to political reasons; it aims even further [50]. Modular, barge-style platforms (about 50×50 m^2), would be assembled in a circular, multicentric design (Fig. **2.16**), forming extended settlements (with an average of 30 inhabitants/platform and over 20,000/settlement), protected by dams. These would be "green" cities, using renewable energy, recycling wastewater, and growing most of their food in aquaponic farms.

Surely, overall costs would be extremely elevated ($10-15,000,000/platform), but there is the advantage of gradual, modular city growth. Besides Polynesia, another area of interest is the Gulf of Fonseca, in Central America, close to the maritime border between El Salvador, Honduras and Nicaragua [51].

A "classical" idea is Aquarius, the modular mound city imagined by M.T. Savage and described above. The proposed building material is biorock (*seacrete*), mostly composed of magnesium oxychloride and produced by electroaccumulating minerals naturally found in seawater (thus, a virtually infinite resource!). Biorock is already in use but requires a high energy consumption (around 1 kWh/kg) and time to produce.

To obtain the energy required, Savage and other advocates of ocean colonization point to another virtually infinite resource: the temperature gradient between surface water (especially in tropical regions) and deep sea. The OTEC (*Ocean Thermal Energy Conversion*) system is nothing but a huge heat pump, sized according to local energy needs [24].

Other available energy sources are water movements: waves, tides, and currents. This is the case of the *Water-Scraper*, a partially submerged settlement imagined by S.A. Bin Sarkum, shaped as a huge carrot-like structure that would use the kinetic energy of water (through a system of mobile “tentacles”), besides wind and solar energy, coupled with aquaculture and hydroponic farming, in a completely “green” city (Fig. **2.16**) [52].

Finally, another interesting project is *Aequorea*, a "green” floating city, designed by Vincent Callebaut, hosting 10,000 housing units on 1,375,000 m^2. The revolutionary aspect is the building material employed for most of the structure: algoplast, a composite material made up of recycled plastic and algal fibers [53].

And there are even more such ideas. Just do a quick search on the Internet and convince yourself!

2.4. THE REALM OF THE ABYSS

Just as landmasses, or even more, the sea should be viewed as a three-dimensional environment. Besides its surface, the bottom and even water layers can become new homes for the human species.

Unfortunately, the benthic environment is still underused. There are some 70 temporary habitats, mostly built for scientific purposes. Starting with the Conshelf 1, 2 and 3 modules, continuing with the famous Sealab 1 and 2, Tektite, Helgoland, Seatopia, Hydrolab *etc.*, such structures were placed in various shallow water areas of the Planetary Ocean. Currently, only Aquarius Reef Base, a small research habitat placed at 19 m depth, near Key Largo, Florida, is still in use. To these, the former tractable research habitat La Chalupa should be added; nowadays, it can be used temporarly, as a mini-hotel.

Besides these, there are some built or close to being built tourist structures (practically, underwater expansions of coastal hotels created for their unique view): Ithaa Restaurant (Maldives), Poseidon Undersea Resort (Fiji) and Dubai Underwater (Dubai) hotels [54].

There is also a mysterious deep sea mining (and, very likely, military) project undertaken by the Chinese government in the South China Sea, although, obviously, very few details are known to the wider public [55].

It is a shame that we have not yet gone further because the underwater environment has the same advantages as the surface one, plus three more. First, the constant climate conditions. Second, the lack of destructive phenomena, such as storms, tidal waves, *etc.* Finally, to the above-mentioned marine resources (accessible food, hydrothermal energy, readily available building materials like biorock and wastes), we can add underwater polymetallic nodules, already exploited in various parts of the world.

There are also some drawbacks. For lighting and oxygenation, the technical means discussed for underground settlements are adequate (Chapter 2.2). Material costs are more elevated because such settlements are completely enclosed. Add corrosion and, especially, the issue of hydrostatic pressure [56].

There are two ways to withstand high pressures. The first option is to maintain the internal pressure close to normal atmospheric pressure, which requires a high resistance of building materials and increases wear, resulting in much higher costs.

The second option is to keep an internal air pressure higher than atmospheric ones (but within acceptable limits to the human organism – not higher than 5-11 atmospheres!). But in this case, whatever the access route from the surface to the underwater colony (tunnels *etc.*) is, it needs decompression chambers. There is, however, the advantage of significantly lower material costs, even to the point of using inflatable structures, just like the portable micro-habitats already used as decompression stations for divers, but at a larger scale [57].

Finally, some concepts of hybrid habitats stretch from the surface to benthic environments. The Anastasi 2032 project, authored by Fletcthel Constructors, involves research, salt mining, water desalination and a sustainable agriculture facility to be placed in the Dead Sea. The cylinder-shaped structure, descending 282 m from the water surface, would host 300 inhabitants and cost around $3 billion (Fig. **2.17**) [58].

Another idea is building mobile habitats, such as *Sub-Biosphere 2*, a settlement made up of spherical modules hosting 100 inhabitants, imagined by Phil Pauley. The whole structure can move up and down some vertical rails, a useful feature during storms, for instance [59].

And if you want to see something even more grandiose, there is the Ocean Spiral city, by Shimizu Corporation, costing an estimated $22 billion and connecting the ocean surface and floor in a massive residential, industrial and research structure (Fig. **2.17**) [60].

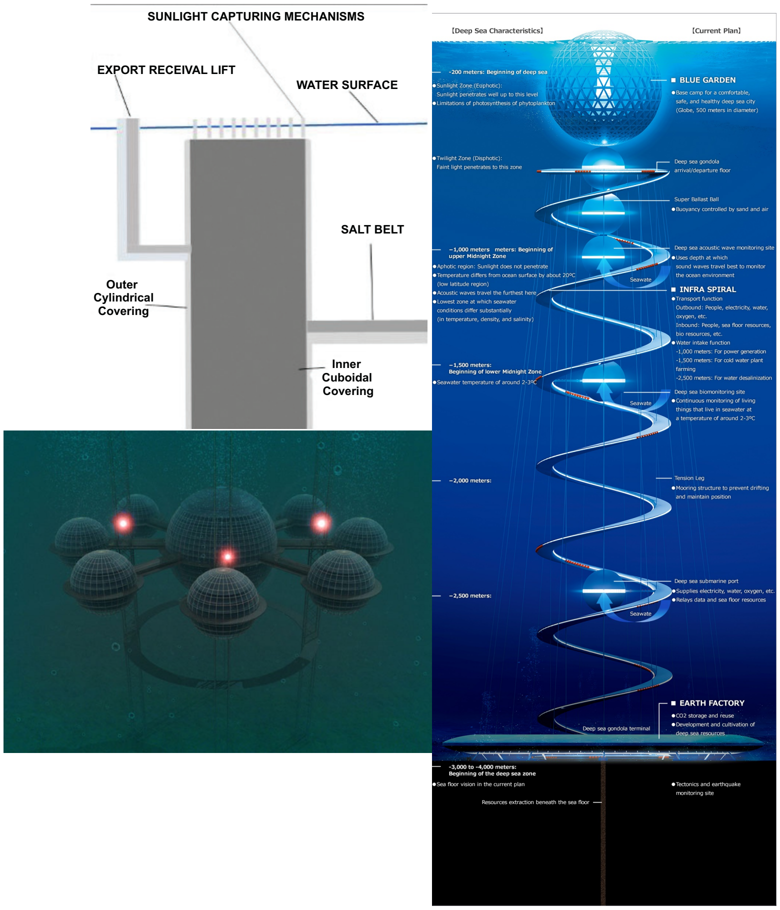
SUNLIGHT CAPTURING MECHANISMS
EXPORT RECEIVAL LIFT
WATER SURFACE
SALT BELT
Outer Cylindrical Covering
Inner Cuboidal Covering
【Deep Sea Characteristics】
【Current Plan】
-200 meters: Beginning of deep sea
●Sunlight Zone (Euphotic): Sunlight penetrates well up to this level
●Limitations of photosynthesis of phytoplankton
■ BLUE GARDEN
●Base camp for a comfortable, safe, and healthy deep sea city (Globe, 500 meters in diameter)
●Twilight Zone (Disphotic): Faint light penetrates to this zone
Deep sea gondola arrival/departure floor
Super Ballast Ball
●Buoyancy controlled by sand and air
−1,000 meters meters: Beginning of upper Midnight Zone
●Aphotic region: Sunlight does not penetrate
●Temperature differs from ocean surface by about 20ºC (low latitude region)
●Acoustic waves travel the furthest here
●Lowest zone at which seawater conditions differ substantially (in temperature, density, and salinity)
Deep sea acoustic wave monitoring site
●Uses depth at which sound waves travel best to monitor the ocean environment
Seawate
■ INFRA SPIRAL
●Transport function
Outbound: People, electricity, water, oxygen, etc.
Inbound: People, sea floor resources, bio resources, etc.
●Water intake function
-1,000 meters: For power generation
-1,500 meters: For cold water plant farming
-2,500 meters: For water desalinization
−1,500 meters: Beginning of lower Midnight Zone
●Seawater temperature of around 2-3ºC
Deep sea biomonitoring site
●Continuous monitoring of living things that live in seawater at a temperature of around 2-3ºC
Seawate
−2,000 meters:
Tension Leg
●Mooring structure to prevent drifting and maintain position
−2,500 meters:
Deep sea submarine port
●Supplies electricity, water, oxygen, etc.
●Relays data and sea floor resources
Seawate
■ EARTH FACTORY
●CO2 storage and reuse
●Development and cultivation of deep sea resources
Deep sea gondola terminal
-3,000 to -4,000 meters: Beginning of the deep sea zone
●Sea floor vision in the current plan
●Tectonics and earthquake monitoring site
Resources extraction beneath the sea floor

Fig. (2.17). Hybrid underwater settlement projects: Anastasi 2032 [59], Sub-Biosphere 2 [59], Ocean Spiral [60].

CONCLUSION

Our civilization has the means to tame hostile environments on our planet. We can use mass irrigation and reforestation in order to make the desert bloom, and we can lighten the skies of the Far North. We can create settlements that combine habitation and agricultural and industrial production in the same space.

We also have the technology to expand on several levels below ground, providing adequate light and ventilation and vertical farming.

Aquatic environments are also perfect targets for colonization, with floating colonies above water level, and submerged ones beneath, harnessing the huge amounts of thermal energy within water bodies and exploiting mineral resources on the ocean floor.

This way, Earth could host many more billions of people, while our society would be ready for the next step: massive settlement of other planets.

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CHAPTER 3

Baby Steps

Earth is the cradle of humanity, but one cannot remain in the cradle forever.
Konstantin Tsiolkovsky

Abstract:

The first obstacle to overcome in large-scale space colonization is represented by the elevated costs of launching payloads into Earth's orbit. The main reasonable solution is using non-rocket space launch methods, which are rather numerous. In the long term, an even more efficient approach is investing in megastructures, such as stratospheric towers, space elevators or orbital rings, that would dramatically ease our access to space, while also allowing us to harness the energy in Earth's atmosphere. Another strategy to support the space race is to make it profitable through space mining. Asteroids and planets host huge deposits of valuable ores, water and fuels, while technical solutions for extraction are already at our ease.

Keywords: Asteroids, Magnetic levitation, Megastructures, Non-rocket space launch, Space mining.

3.1. BREAKING OUT OF THE EGGSHELL BREAKING OUT OF THE EGGSHELL

The moment has come to look above us! Our planet's atmosphere and the extraterrestrial spaces are neither barriers nor mere research targets, but an ensemble of practically infinite resources.

Earth's orbit is a somewhat familiar environment: more than two thousand artificial satellites are in continuous revolution around the planet, one of them being the International Space Station. Plus a lot of "space junk", of course.

Yet, space launches are not really at our ease. They are not part of our current life. From this point of view, we are in the same situation as our Stone Age ancestors when they started exploring the sea. Some did adventure, but rarely and not far from shore. And there is a reason for all this costs.

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Currently, the entire aerospace fleet of humankind is based on thermo-chemical propulsion engines. Basically, the violent oxidation of a certain fuel produces hot gases with a fast dilation, whose ejection generates thrust. However, there is a problem: Earth has a gravitational force that tends to slow down and pull down any vehicle launched from its surface. And there is more: the atmosphere has its own friction force that also brakes spacecraft.

The current solution is to add some extra fuel, in order to compensate for the two hostile forces. But this extra fuel has extra mass, making the vehicle heavier. To propel the supplemental fuel, a new amount of fuel is necessary. This fuel also has its own mass.

You have surely seen images of space rockets. In reality, only their "tip", the capsule, is the one carrying the payload. The rest are detachable stages filled with fuel. Similarly, for space shuttles, only the shuttle itself and the side boosters are reusable, not the huge external tank.

The overall costs of necessary fuel and building materials are enormous. Launching one kilogram of payload into Earth's orbit costs at least $12-15,000!

Obviously, there is some recent progress in the field, mostly through SpaceX's reusable rocket technology. For the moment, launch costs have decreased to some $5,000/kg and even $2,000/kg, with the new Falcon Heavy model, and the company leadership aims to a further drop to around $1.000/kg, in the next few years [1, 2].

However, if we really want to become a multi-planetary species, we should probably find a more convenient alternative to classic rocketry. And there are a few useful ideas.

One that Jules Verne would surely find appealing is the ballistic space launch. Basically, we should call in the heavy artillery! The advantage of a cannon is that combustible materials, those creating thrust, are to be found at the ground site, inside the launching device. They do not need to be carried by the projectile, thus no more of that bothering progressive weight increase effect described above.

By "cannon" we could, obviously, mean any explosive ejection device. In 1961, a team of researchers from McGill University, Montreal, led by Dr. Gerald Bull, in collaboration with the US Army's Ballistic Research Laboratory, initiated Project HARP (*High Altitude Research Project*). Three huge cannons were tested, with calibers of 406-410 mm and 20-41 m barrel lengths. One of them managed to send a 180 kg projectile at 180 km altitude, before the project was cancelled in 1967 [3].

Although HARP was never resumed (the unfortunate collaboration of Dr. Bull with Saddam Hussein was, probably, one of the reasons), there was a second version: SHARP (*Super High Altitude Research Project*), initiated in 1985. In this case, a mixed system, with chemical (methane) ignition and compressed gas (namely, hydrogen), was employed. The projectile was propelled through a 47 m barrel (the primary barrel and the compression pump attached had a total of 82 m!) and launched up to 130 km, at an impressive speed of 3,000 m/s. Only small-sized projectiles (5 kg) were used, SHARP being only intended as the first step towards larger launchers (unfortunately, this project also got "stuck", due to financial reasons, in 1995) [4].

SHARP's "father", Dr. John Hunter, unsuccessfully tried to resume the program as a private venture. Quicklaunch company designed a 1-km-long compression launcher, for massive projectiles. This would have ensured a launch velocity of 6,000 m/s, which would have been supplemented by triggering a rocket engine at a high altitude (11,000 m/s is the escape velocity needed for the escape Earth's gravity). Due to the intense 5.000 g acceleration, this method could be only used for inert materials – satellites, building materials, supplies *etc.* – 9 g being the maximum value our body can withstand.

Still, such a launcher would decrease payload costs to $125-250/kg! But only if its designers manage to raise the initial funding needed [5].

During the same period, scientists in the Soviet Union also researched the possibility of using mega-cannons as orbital launchers. In 1976, T. Bakirov and V. Mitrofanov imagined a *blast wave accelerator* – a cannon bearing circular explosive charges, at regular intervals along the barrel. These would be able to progressively accelerate a projectile, up to incredible speeds. An 861-m-long and 576 mm caliber cannon could launch 1,000 kg vehicles (250 kg being their payload), up to 8,000 m/s.

There is also the possibility of using "mechanical", sling-style acceleration. The *Slingatron*, imagined by D. Tidman in 1995, would be composed of a spiral barrel, subjected to circular oscillations due to engines placed at regular intervals (Fig. **3.1**). There is no need for major oscillation amplitudes for the projectiles to be accelerated at each curve of the spiral. For accelerating a 1,000 kg projectile to an 8,000 m/s launch velocity, a 45-km-long barrel (the resulting spiral would reach 500 m in diameter), 330 mm caliber, oscillating at 75 m/s would be enough. With absolutely no need for any fuel [6]!

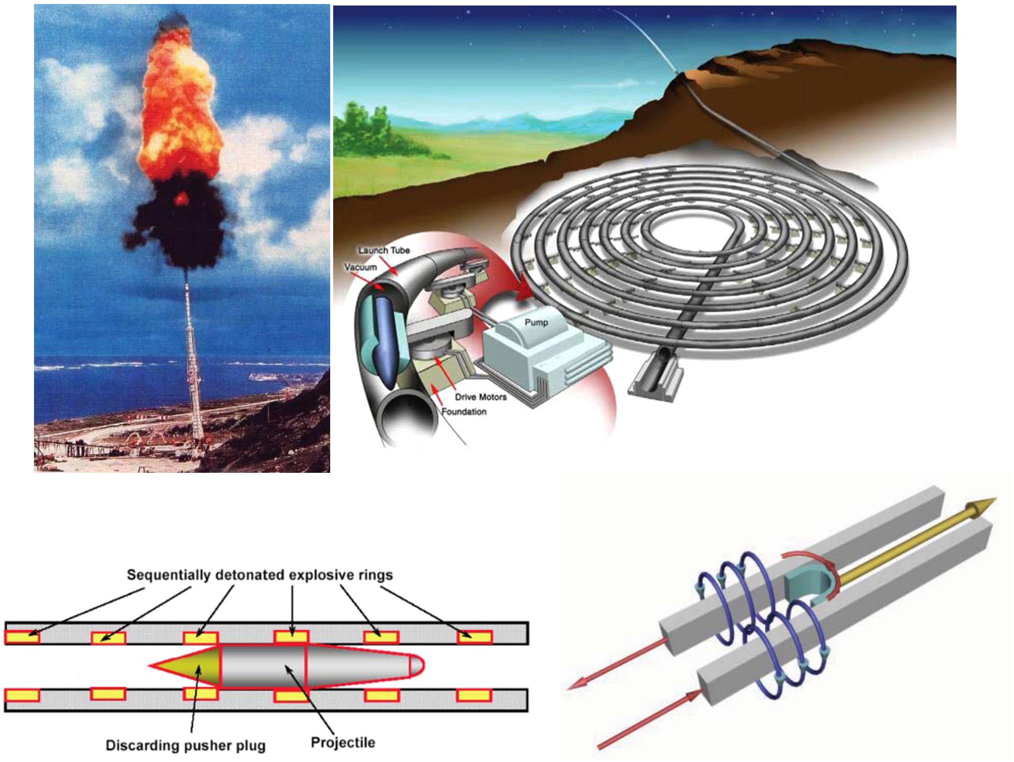

Fig. (3.1). Non-rocket space launcher projects: HARP, Slingatron, blast wave accelerator, electromagnetic levitation railgun [6].

A modern alternative (even though rather energy-consuming) is electromagnetic levitation launchers. Basically, they use the same technology as MagLev high-speed trains.

There are two options considered. A railgun would accelerate the vehicle by magnetizing two lateral rails, due to high-amperage electric currents. This is the classical MagLev technology that allowed reaching, under laboratory conditions, exit velocities up to 7,000-9,000 m/s.

The coilgun, instead, is only in its first phases of experimentation. In this case, thrust is generated by magnetizing spiral rails. In theory, this has the advantage of not having any physical contact point between the projectile and launcher, thus eliminating any friction force or material wear. Yet, small-scale experiments have not yet produced exit velocities higher than 1,000 m/s [7].

Logistical problems, in this case, are due to the total size of the launching device (tens of kilometers of barrel length, ensuring enough acceleration), its electricity consumption, and positioning. To reduce friction and fuel amounts necessary for secondary propulsion but also to cool down the barrel, its terminal sections should be built on the slopes of a mountain range (Fig. **3.2**).

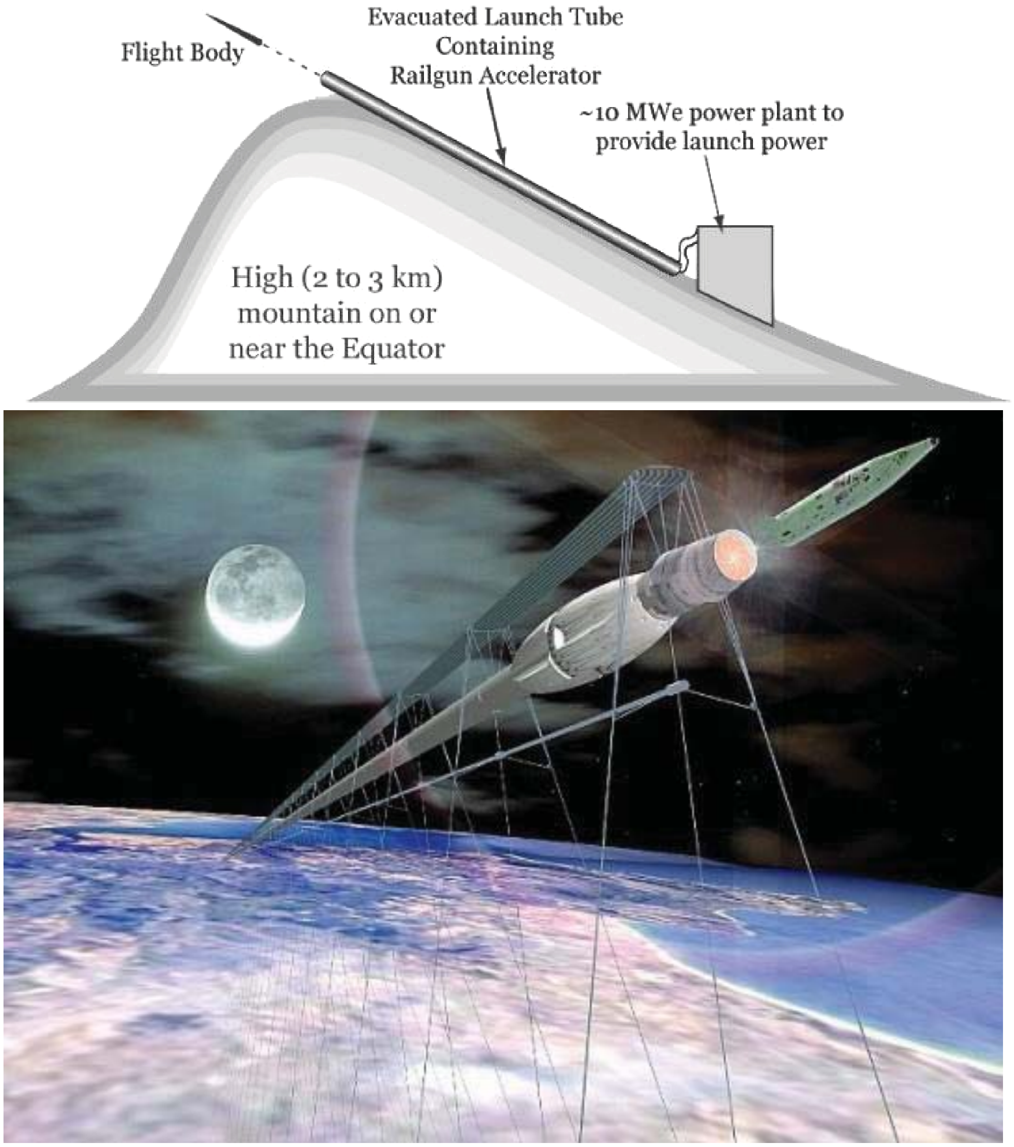

Fig. (3.2). The basic design of an electromagnetic orbital launcher (railgun) [7] and an image of Project StarTram [9].

Preferably somewhere close to the Equator, also for orbital insertion efficiency. M.T. Savage chose it as an ideal area for a giant railgun launcher (Project Bifrost), Mount Kilimanjaro or Kenya [8].

Yet, there are some effective solutions at our ease. A UTSTAR modular launcher, 1,600-m-long, could propel 1,250 kg vehicles (around 300 kg payload) at exit velocities of 7,500 m/s, requiring an electricity source of just 10 MW (basically, less than 1% of an average nuclear power plant)!

Surely, those vehicles would need their own propulsion systems, for accelerating above 11,000 m/s, maneuvering, docking, *etc.*, but the final costs would amount to about $530/kg [9].

But that is just the beginning since we may use even more convenient approaches to this problem! We can, of course, build MagLev rail launchers on mountain slopes, but Earth's landscape always imposes a limit. So, what if we extended these systems even further into the atmosphere? It sounds a bit crazy, but we can do it using the same magnetic levitation process.

It is the idea behind the *StarTram* concept, proposed by James Powell and George Maise. StarTram has two versions. The first generation of launchers would follow the above-mentioned model and would only function for inert payloads. A railgun (but with its barrel kept under complete vacuum) would be erected on the slopes of a 4,000-6,000-m-high mountain (several areas in the Chilean Andes and Southwestern USA were proposed). It would cost around $20 billion, but it could launch 40-ton vehicles, at 8,800 m/s and 20 g initial acceleration each hour, lowering overall launch costs to an impressive $20-50/kg.

The second generation would be dedicated to passengers. In this case, the tube would be extended up to 20 km altitude. The extra segment would be maintained in position by magnetic levitation using a large network of superconductive cables. At that altitude, high exit accelerations would not be required anymore, thus removing any unpleasant effect on human passengers. All this would cost around $60 billion (this is a raw estimate; there is always the possibility of final costs increasing up to $70-90 billion) and 20 years to build.

Due to its size and payloads, the launcher would require 50-100 GW of electric power, which is a large amount (more than the output of the world's eight largest power plants combined), but not impossible. However, it would result in a true revolution in spaceflight: millions of colonists could leave Earth yearly [10, 11]!

For the moment, a quite mysterious company, SpinLaunch having behind some serious investors, including Google Ventures and Airbus retrieved the idea and is raising funds to initiate building such an electromagnetic launcher [9].

20 km altitude seems a lot, but in order to truly become a spacefaring civilization, we might need to get used to even more staggering heights. Space elevators still sound like an SF theme, with numerous technical issues to overcome. To reach geostationary orbits, 35,000-km-long cables are necessary without including the counterweight. Such structures should also support their own weight, as well as atmospheric turbulence.

For now, Obayashi Corporation, a Japanese construction company supported by the Science Council of Japan and other scientists and government agencies, is trying to take the first steps. A small-scale experiment concerning material resistance took place in 2018. The final goal is to build up a cable system of over 96,000 km (made up of carbon nanotubes, a material still in its concept stage), costing around $90 billion and lowering launch costs to $200/kg [12].

Fortunately, there is a more feasible and easily accessible alternative for our current technological level. It is called *SpaceShaft*, a concept ideated by Nelson Semino and Patrick Vankeirsbilck, who also founded a company dedicated to fundraising, designing and initiating the construction of this megastructure.

SpaceShaft is a huge tower made up of conventional building materials: metal, Kevlar, Mylar *etc.* The outer wall of the structure would be multilayered, with numerous lighter-than-air gas-filled chambers. The revolutionary idea behind this concept is that the whole tower would be "extruded” bottom-up. As a new section is being built, the "baloons” from its outer wall would lift it, so the new section could be assembled below (see Fig. **3.3**) [13].

This way, the proponents aim to erect a 30-50 km tall tower, possibly extending it up to 100 km altitude or even higher. This is, practically, the upper limit of the atmosphere, where low gravitational pull and, mostly, the lack of any noticeable friction force would make space-launch incredibly convenient.

As lifting gas, you probably think of helium. Well, so did the authors of this project, but the costs would be high, and about 35% of Earth’s annual helium production would be necessary (note that helium resources are on the verge of depletion, anyway). The second revolutionary idea is the *Hypercubes*, cuboid "baloons” filled with "virtual vacuum”. The information made available to the public consists of gas (primarily helium) kept at very low pressure. Lower sections would be laterally tethered using metallic cables (for stabilization). The whole structure would cost "only” €130 million [15]!

Fig. (3.3). "Extrusion" process of the SpaceShaft tower [14].

Furthermore, structures like StarTram or SpaceShaft have an extra advantage: they pave the way to colonizing the atmosphere and exploiting its resources. The atmosphere is much more than just an air reservoir; its main resource is electricity.

The idea of using air as an energy source is quite old, dating from the 18th Century. Nikola Tesla also tried, unsuccessfully, to explore this virtually endless resource. However, modern technology allows us, now, to do just that.

There are two ways to harvest atmospheric energy. The first one is to use thermoelectric processes – basically, harness temperature gradients, just as heat pumps and OTEC systems do underground in the ocean. There are already some experimental devices capable of doing it at a small scale [16].

The second option is to directly harvest atmospheric ions. This is what Ion Power Group, a private enterprise, wishes to accomplish by using a network of mini-collectors made of graphene and graphite, carried by floating structures like balloons and kites. The procedure is already being tested, results seem promising, and the cost is impressively low [17].

However, all these solutions are suitable for the lower atmosphere. Things will change dramatically once we get access to higher layers, more precisely, to the ionosphere. The ionosphere comprises parts of the mesosphere, the thermosphere and the exosphere, which means from 60 km altitude to the lower limits of space. It is the place where incident solar radiation causes the mass ionization of local particles, forming enormous electrical circuits whose visible manifestations are lightning.

Together, all these circuits in the terrestrial atmosphere amount to an incredible 2×10^{10} J energy [18]. Building structures tens of kilometers tall, or even over 100 km (such as SpaceShaft), would give humankind easy access to this limitless, free and absolutely "green” energy source.

Besides rail launchers, towers and elevators, another important option for the future of our civilization is floating air structures. Helium balloons are already tested as platforms for space launches. A company called Zero 2 Infinity provides such services for launching satellites and other types of payloads into Earth’s orbit: Bloostar systems can carry self-propelled capsules up to an altitude of 30-40 km, resulting in major fuel savings [19]. In Romania, ARCA company tested the Helen hybrid (balloon-rocket) reusable spacecraft [20].

On the other hand, the idea of regular air transport using dirigible balloons is also gaining terrain. Project SkyCat (*Sky Catamaran*), with its smaller-sized version, creatively named SkyKitten, made some impression at the beginning of this century, before the ATG company went bankrupt. We are talking about massive airships capable of carrying payloads heavier than 50 tons [21]. The project was retrieved, in 2007, by the British venture Hybrid Air Vehicles and transformed into HAV-3, respectively Airlander 10 – a 44-m-long airship, carrying 10 t payloads – currently planning to build the Airlander 50 (obviously having a 50 t payload, or 200 passengers) [22].

And now, by connecting rigid megastructures, such as StarTram, SpaceShaft or different versions of space elevators with floating structures at an even larger scale, could not we envision a global network of atmospheric structures? Power plants, launch sites, research facilities and even permanent settlements. An entire vertical expansion of humankind, this time going upwards! Of course, as mentioned above, helium is a limited resource here on Earth, and it needs to be used cautiously. But the opening of extraterrestrial space would offer new possibilities. Jupiter, Saturn, Uranus and Neptune all have enormous amounts of helium in their atmospheres.

Furthermore, besides "baloons”, large and small, we can always use magnetic levitation.

In 2012, an architect named Wei Zhao created the "Heaven and Earth” concept (*Tian-Shan-Ren-Jian*), which won a dedicated competition. It is a circular city, hosting housing units, farms, parks, and even small water bodies- a totally eco-friendly city. All these are built onto a ring-shaped, electromagnetically-levitated platform, kept stable through continuous rotation (Fig. **3.4**) [24]. An energy-consuming design, obviously, but not if we manage to harvest the huge amounts of electricity in Earth’s atmosphere. Not to mention that the idea of "floating” cities will prove useful, for instance, in the initial stages of colonizing planet Venus, as you will find out in Chapter 7.

Fig. (3.4). Floating or hybrid aerospace structures: Helen [20], Airlander 50 [22], Bloostar [23], Tian-Sh--Ren-Jian (electromagnetically-levitated city) [24].

Yet, the apex of aerospace mega-engineering would undoubtedly be represented by *orbital rings*. Orbital rings are an alternative to space elevators, but reaching much lower orbits than geostationary ones (over 35.000 km). There are various types proposed: high-orbit, eccentric orbit, or low-orbit rings, where "low” means somewhere from 2,000 km and down to "just” 450 km or even 300 km above the ground [23, 24].

Neither of these ideas is really a new one. Back in 1963, the US Department of Defense and US Air Forces initiated an experimental phase of Project West Ford: a ring of mini-transmitters (basically, 1.8-cm-long copper filaments) to orbit around Earth, ensuring communication continuity in case of a Soviet nuclear strike [25].

An orbital ring built for transportation purposes would be much more complex. First, it would require space stations placed at regular intervals in low-Earth orbit and connected to the ground through elevators (although some imagined using giant rotating "slings” – the so-called Sling-on-a-Ring concept – that only descend down to 13 km altitude [26]). On such an orbit, however, stations will not be actually stationary, tending to revolve around the planet, with extremely unpleasant effects on connection tethers.

There are two ways to maintain terminal stations in stable positions. The first option is to have a discontinuous ring, such as that imagined by David Nelson. In this case, a group of satellites would continuously launch, one towards another, 40 aluminium projectiles, with up to 30 km/s velocities. These "passes” would stabilize the orbital platforms and allow connection tethers to be built (these, in turn, would support elevators: mechanically/electromagnetically propelled capsules). At an altitude of 450 km, tethers could be built using materials like Kevlar or Zylon, and the whole ensemble would cost some $8,9 billion – an elevated cost, but rather convenient, considering the benefits [27].

A continuous ring would mean connecting orbital platforms through a rigid structure (bascially, the platforms would slide through magnetic levitation, the ring itself rotating at speed a bit higher than the orbital one; in compensation, platforms would remain geostationary) and then connecting them to Earth’s surface through space elevators (Fig. **3.5**).

Although in most SF novels and Internet imagery, orbital rings are massive, hollow structures, providing plenty of living space inside, a simple metallic rail would be just enough!

The advantages are huge. First, the costs for orbital insertion of various payloads would drop to $10/kg, a tiny sum that would likely also offer a convenient alternative for Earth-to-Earth transportation, with a small orbital detour. The ring could be connected, using mobile cables, to a plethora of satellites. It could host and connect solar power plants, launch sites, industrial platforms, farms and even permanent settlements. Rings could be used to extract huge amounts of valuable gas from giant planets and even to terraform Venus [28].

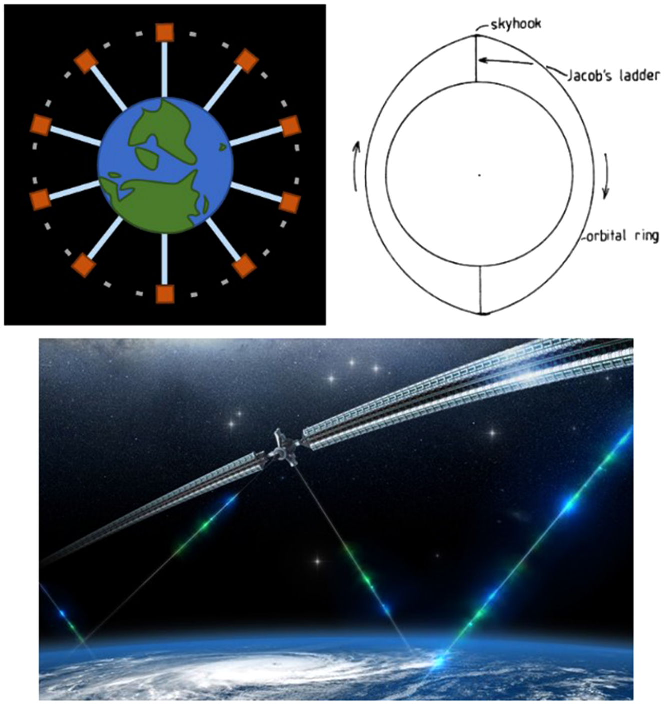

Fig. (3.5). Schematic of discontinuous [27] and continuous [28] orbital rings; a conceptual image of such a megastructure [30].

Once a ring is built around a planet, the next ones can be assembled at a fraction of the initial costs. And a discontinuous ring can be easily converted to a continuous one.

Applications are endless. They could anchor ocean spiral cities, mine gases from other planets, support orbital mirrors for terraforming purposes, provide a starting point for creating "shellworlds" (planets/planetoids with enclosed breathable atmospheres), or even ultra-futuristic things, like "Matrioshka Brain" mega-computers or stellar engines [29]. Orbital rings are a great way to definitively "anchor" human society into the Cosmos!

3.2. Mines of the Future

One of the main forces that will drive humankind to space in the future is the need for resources. And, most of all, mineral resources. We already saw, in (Subchapter **1.2**), the current problems concerning the scarcity of various metals and other valuable chemicals. A continuously-growing civilization with a growing industry, means a growing demand for such raw materials.

Thus, the way to space (also) passes through the mining industry!

And many big companies already chose their target. Small-sized celestial bodies, rich in minerals and other key resources, with extremely low gravity, posing little problems to landing and launch and which can, if necessary, be moved through the Solar System as we wish. Yes, you guessed it: we are talking about asteroids.

Actually, the generic term preferred by astronomers is *minor planets*, a term that comprises a wide range of bodies revoluting around the Sun, on various types of orbits. There are millions of such objects, with sizes ranging from a few millimeters up to over 1,000 km.

Proper asteroids are considered those having a solid structure, but besides them, there are meteoroids – bodies below one meter in diameter – as well as objects formed predominantly of ice (not necessarily water ice!), including iceteroids, comets and the plethora of Kuiper Belt and Oort Cloud objects (found at the very edges of the Solar System).

Some periodically collide with other bodies, including Earth, creating beautiful "shooting star” showers (the best case) or catastrophic events (the worst case). The time has come to give them a new use!

Between 1,000 and 1,200 such objects, with a diameter higher than 1 km (plus a multitude of smaller ones) form the so-called *Near-Earth Objects* group (shortly, "NEO”; Fig. **3.6**). Also relatively "close” to Earth, we may find the main Asteroid Belt, located between the orbits of Mars and Jupiter, plus the "Greek” and "Trojan” asteroids, found in the vicinity of Jupiter’s orbit.

Basically, these asteroids can be divided into three main classes, considering their light emission and reflection spectrum, and thus, their composition. C-type (about 75%) comprises carbonaceous asteroids, dominated by rock (mostly silicates, feldspars *etc.*), followed by water (around 20%), and hydrocarbon complexes (10%, mostly polycyclic aromatic ones). S-type includes rocky asteroids formed of rock (mostly iron and magnesium silicates), sulfides, and metals. X-type has many subclasses, the most important being M-type: metallic asteroids, dominated by iron, nickel (together forming up to 90% of the total mass) and other metals, often found in their pure state, plus higher or lower percentages of rocks. They can contain up to 5% rare, precious metals belonging to the platinum group [30 - 32].

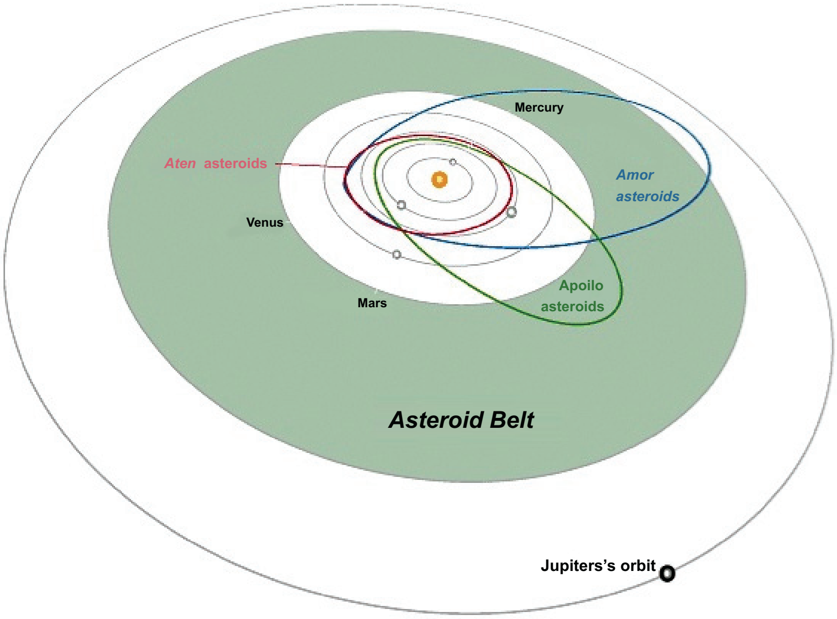

Fig. (3.6). The main asteroid concentrations around Earth [31].

Of course, the most wanted targets are metallic asteroids. A medium-sized asteroid could contain more metal than humankind has ever mined in its entire history. They are mostly iron, nickel, cobalt and some other pure elements (thus, easy to refine), extremely useful in about all industries.

Besides them are rare elements, like gold and platinum-group elements. Although you would probably think of jewels, nowadays, these elements are used on a large scale in producing circuits, electrodes or catalysts for various chemical reactions (obtaining hydrogen, for instance). Currently, these metals are being extracted quite inefficiently, with a large amount being lost as waste. At this pace, Earth will soon run out of platinum and similar metals [33].

In space, though, platinum-group metals are about as common as lead. A single M-type asteroid, 500 m in diameter, could contain 174 more platinum than Earth's annual output and 1.5 times more than all known deposits [32]!

However, metals are not the only valuable resources. In space, water and various volatiles (ammonia, for instance), can be as valuable, as fuel sources. They can also be used in agriculture, space structures (water provides good radiation shielding), and planetary ecological engineering processes, including terraforming, as we will find out in the following chapters.

Finally, various minerals can be used in building space structures, or even for soil enrichment, for supporting the agriculture of future extraplanetary communities. And, sometime in the future, asteroids themselves could host human settlements [34].

Technically speaking, extracting valuable materials from asteroids consists of several phases. First, there is prospection: identifying valuable asteroids, with suitable sizes and their position within the Solar System, as well as the specific area of each asteroid where resources of interest are more concentrated. Basically, it is assumed that mineral concentration in asteroids is relatively uniform, except for some elements that are mostly found in surface regolith, either in its finer or in coarser fractions.

Then follows excavation (using mechanical, magnetic or pneumatic methods), eventually "capturing" and transporting the entire asteroid. Then, processing, though grinding and/or concentrating the material. Concentration can be achieved by magnetic means (in the case of ferrous metals) or electrostatic ones, separating metal dust from larger fragments.

Extraction can also be done by thermic or chemical means, in the case of carbonaceous or rocky asteroids (evaporating volatiles, separating titanium from ilmenite *etc.*), or just thermic means, for purely metallic asteroids. In the latter case, dealloying metals in space can be troublesome, so specialists recommend using metal dust for 3D printing and transporting metals under this form. Finally, storage can be done by attaching the extracted metal to the transporter-probe, respectively, by accumulating water and volatiles in pressurized tanks (Fig. **3.7**) [34].

There are already some private ventures and government agencies that are showing interest in this field. Among them, Planetary Resources (having as investors a large part of Google owners, but also Virgin and Bechtel), Deep Space Industries (DSI; an Australian venture), Kepler Energy and Space Engineering (KESE), but also the American government and, especially, the government of Luxembourg. The two governments already adopted legislative acts to regulate activities of this kind and the Grand Duchy of Luxembourg also signed various agreements with companies like DSI and with the governments of Japan, Portugal, United Arab Emirates and Russia, in order to turn the small European state into a true hub of space mining [35, 36].

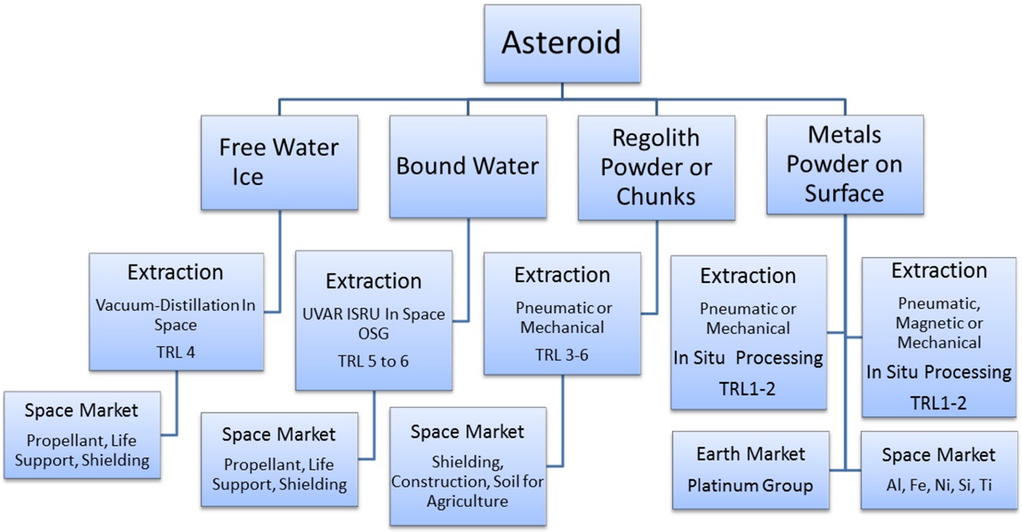

Fig. (3.7). Resources found on asteroids, their processing and usage pathways [34].

Let's see, briefly some technical solutions envisioned for such activities (see Fig. **3.8**)! It must be said that some preliminary prospection missions were already completed, like Hayabusa 1 and 2 or Rosetta. The Japanese Hayabusa 2 probe, for instance, successfully completed a rendezvous with asteroid 162173 Ryugu, in 2018. It shot a 2-kg copper projectile at the asteroid, collecting the resulting debris (including material from surface regolith layers) and returned to Earth for analysis in December 2020 [37].

Planetary Resources designed the Arkyd probe class. In a first phase (Arkyd 100-300), it included cube-shaped, low-cost microsatellites that can operate in swarms (Arkyd 300) and whose mission will consist of prospecting the chemical composition of target-objects and, very important, marking them as future exploitations of the company (to prevent similar claims from competitors) [32, 35].

PR also designed an innovative probe for extracting water and volatile compounds. This can inflate as a cylinder-shaped bag, engulfing the asteroid and using solar energy to heat it and extract the compounds of interest (Fig. **3.8**). Unfortunately, the company is under reorganization, with a change in shareholding (obviously, due to financial reasons), so that the completion of its programs is still uncertain.

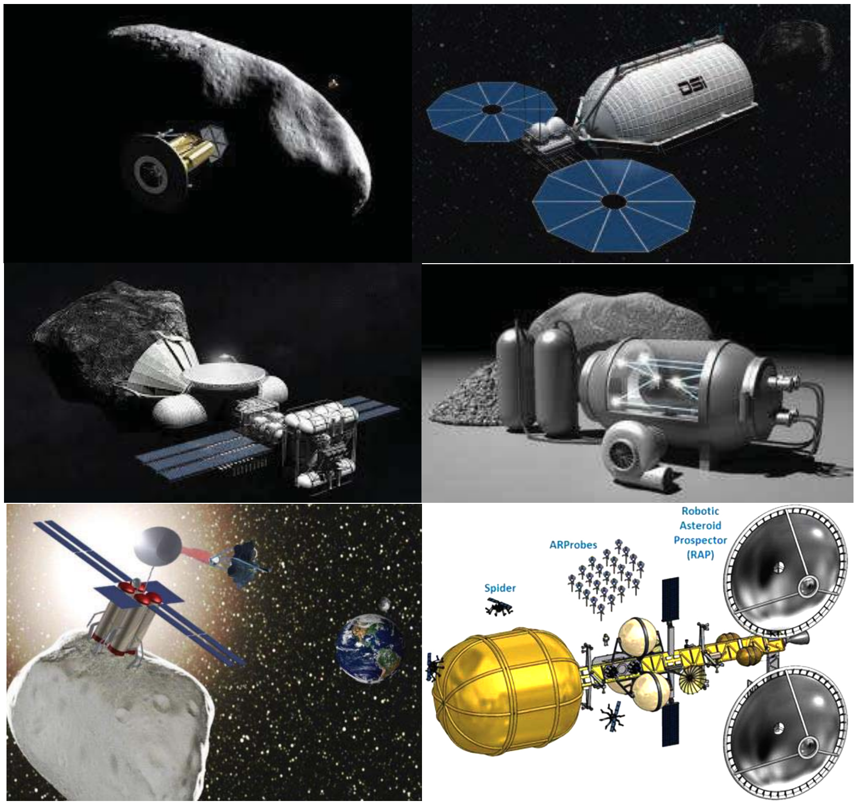

Fig. (3.8). Several types of devices designed for space mining: Arkyd 200 Interceptor (Planetary Resources) [32], Harvestor-1 bag-probe for volatile compounds [38], fuel refining center [35] and foundry plus microgravity 3D printing facility (Deep Space Industries) [32], Cornucopia drilling probe (Kepler Energy and Space Engineering) [39], Robotic Asteroid Prospector (NASA) [34].

DSI, also facing a recent change in shareholding structure, developed several interesting concepts, including prospection probes Prospector-X and Prospector-1, respectively bag-probes for water extraction Harvestor-X and Harvestor-1. An *in situ* refinery and fuel production station should be added [38].

The main dedicated project of KESE is Cornucopia, an autonomous robotic system, packed with drilling and regolith compacting devices and four autonomous transport modules, each having the purpose of bringing back to Earth the material collected (a total of around 40 tons per probe) [35, 39].

Finally, the Robotic Asteroid Prospector (RAP), designed for NASA, is much more than its name would imply. This probe, mostly dedicated to water extraction, can process small asteroids (below 20 m in diameter), release reconnaissance probes, and robotic devices for extraction and retrievement

(Spider) [34].

Furthermore, a feasible alternative is capturing valuable asteroids and bringing them to circumterrestrial orbits, in order to facilitate mining. We can imagine, somewhere in a not-so-distant future, such bodies orbiting around our planet (maybe serving as counterweights for space elevators or being connected to orbital rings), constantly supplying us with raw materials, serving as launch sites or even as habitats [40, 41].

Asteroids can be much more than moving mines. Here is, for instance, the RAMA Project, involving a "seed craft" that would land on an asteroid and excavate it, using laser drills, until all valuable materials inside are extracted and refined. After that, a reactive torus would be placed at one end to rotate and stabilize the asteroid, which would be ready to be propelled through space (using rocket engines or mass drivers that use local material as propellant). Once brought into orbit, the empty "shell" could be transformed into a habitat (similar to underground ones described in Subchapter **2.2**), which would also feature artificial gravity, due to continuous rotation [42].

In this effort to move asteroids through the Solar System (as we will see below, they are also of great importance to planetary settlement), we could use an unjustly forgotten technology. We are talking about the nuclear-thermal rocketry, more precisely, the Rover/NERVA (*Nuclear Engine for Rocket Vehicle Applications*) program, conducted mainly at the Los Alamos military nuclear facilities between 1955-1973. Tests have shown a continuous increase in engine efficiency, until, the project was terminated, due to financial and political reasons.

Briefly, in such an engine, a nuclear reactor (up to 1,000 MW or over) heats the fuel until it reaches extreme temperatures and pressures, and its ejection can produce thrust. Five decades after the program was halted, more and more experts began to consider NERVA as the key to conquering the Solar System. But what should be the necessary fuel? Well, here is the good news: any kind of gas, liquid or other chemicals that can be evaporated at those temperatures will do, including compounds that are easily found in asteroids (water, ammonia *etc.,*) [43].

But not just asteroids can prove useful to the mining industry. For example, although few details are known yet about the lunar regolith, there are strong clues that it could harbor interesting resources.

First of all, ^{3}He isotope, slowly accumulated in eons, due to Moon's surface interaction with the solar wind, could soon become a key resource for nuclear fusion reactors (note that we do not harness controlled fusion technology yet, although important steps are being taken in that direction). This could be the main energy resource of the future! The main areas with high ^{3}He concentration (the oldest areas of the lunar crust), Mare Tranquillitatis and Oceanus Procellarum, could contain, as an estimate, around 200,000,000 kg of this gas [44]!

Add to this water, mainly concentrated in circumpolar craters and oxygen, as raw materials for fuel production. The latter can be refined from common minerals, such as ilmenite and silicates, through hydrogenation, respectively hydrolysis or destructive distillation (though all these processes are quite energy-consuming) [45].

There are some metals, such as iron, that are difficult to extract from silicates and less abundant as free elements in the regolith, but still in remarkable amounts. On the other hand, titanium is much more accessible and could be extracted from ilmenite deposits, together with oxygen. Aluminium, silica, lanthanides, uranium, thorium, and platinum-group metals are also quite abundant, as it seems [44].

Other resources await us on Mars (iron, titanium, vanadium) and Mercury (magnesium, calcium). The atmospheres of gas giants (Jupiter, Saturn, Uranus, Neptune) are ideal sources of hydrogen and helium (including isotopes ^{3}He and ^{4}He, for nuclear-electric applications). In this case, we could rather use massive airships to float in the outer atmospheres, extracting and concentrating gases of interest [46].

Finally, let's not forget Titan, Saturn's main moon, harboring seas and lakes made of hydrocarbons (mainly ethane, methane, and propane). It is a place where natural gas literally rains from the sky, and thanks to the Cassini probe, we know quite well the distribution of these resources [47].

CONCLUSION

The first step towards becoming a spacefaring civilization is rethinking the way we get into orbit. Railguns, coilguns, slingatrons or dirigible-assisted launches, all seem feasible approaches.

A step further, creating a substantial atmospheric and extra-atmospheric infrastructure (StarTram, inflatable stratospheric towers, space elevators and, most of all, orbital rings) would mean a revolution in space transportation and not only, definitively anchoring humankind into space, helping us bypass the atmospheric barrier and providing limitless amounts of energy.

On the other hand, the current drive towards space mining also has the potential to revolutionize our society. The exploitation of metal-rich asteroids would provide enough raw materials to meet the demands of a growing and developing civilization, including the resources needed to build various megastructures. Heavy helium isotopes pave the way for cheap fusion energy, while other volatiles would help us fuel huge space fleets, and feed various colonies in the Solar System while also proving crucial for planetary engineering projects.

But, most of all, profit would boost the public and private space industry sectors. Mining probes would be soon followed by processing plants, human personnel and proper settlements.

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CHAPTER 4

The Red Planet

Certain harmonies could be set up here along self-sustaining lines.
You merely have to understand the limits of the planet and its pressures.
Liet Kynes (character of the Dune series, by Frank Herbert)

Abstract:

Among the planets in our Solar System, Mars is the closest to Earth in terms of distance and similarity. However, current environmental conditions on its surface are hostile to any life form. While it provides enough space for sheltered, enclosed settlements, the final goal should be terraforming the Red Planet, which is perfectly achievable at our current technological level.

Terraformation consists of two stages. Ecosynthesis (creating conditions for microbial life) can be accomplished within a century, by a synergistic approach using nuclear blasts, greenhouse gasses, orbital mirrors, thermal aquifer drilling, directed asteroidal impacts, *etc.,* Caeliformation (creating a breathable atmosphere for humans) would take several centuries, involving the controlled introduction of terrestrial life forms and atmospheric conversion through photosynthesis. Even after that, a continuous effort would be required to ensure habitability in the long term.

Keywords: Caeliforming, Ecosynthesis, Mars, Microbial colonization, Photosynthesis, Terraforming, Warming.

Mars has always captivated the imagination of humans and, especially, scientists (Fig. **4.1**). Located at 1.52 astronomical units from the Sun (AU; where an astronomical unit is equivalent to the distance between the Sun and Earth), with a lower mass than Earth and an adequate gravity (0.38 g – 38% of the terrestrial one), having a year of 687 Earth days, with each day surprisingly similar to ours (one terrestrial day and 37 minutes!), Mars is considered to be the most "habitable" planet besides ours.

Dan Răzvan Popoviciu
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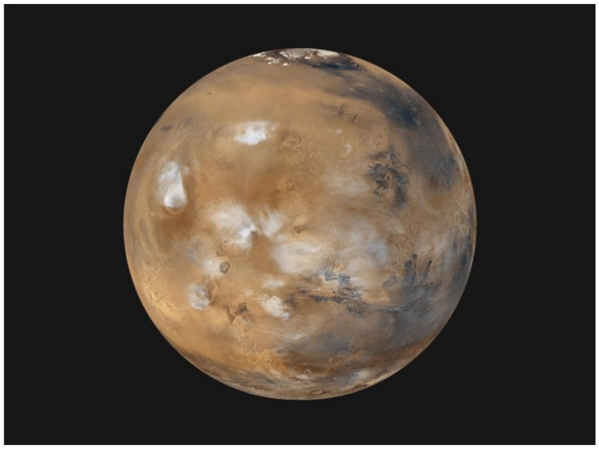

Fig. (4.1). Mars seen from space; the northern polar cap and the huge Valles Marineris canyon are visible [1].

And there is more and more proof showing that hundreds of millions of years ago, the planet had a dense atmosphere, a mild climate and vast water bodies, both still and moving. Maybe even life, who knows? After which things went crazy. We do not know the cause, maybe a major asteroid impact, the loss of the planet’s magnetosphere, causing the slow atmospheric erosion due to solar wind. Either way, Mars entered an extreme ice age: the remaining atmosphere froze or got "lost” somewhere in the crust or space, surface water disappeared, and average temperatures dropped to around -60°C (+15°C being the average value on Earth).

Today, Mars is a cold, sterile world, with an atmospheric pressure of 0.8 kPa (compared to 101 kPa on Earth), covered by a red regolith („soil” analogue plus surface rocks), rich in iron oxides but continuously showered by cosmic radiation and unwelcoming to any life form due to high amounts of peroxides. Yet, we know there is groundwater, periodically bursting though the surface (last flow traces are less than one million year old!), water, and carbon dioxide ice in the polar caps and regolith [1, 2].

Although many scientific probes were sent there, the effort to reach Mars never went past this level. Even though there have been years of discussion about possible human missions on the Red Planet, for scientific exploration, exploiting its quite remarkable mineral resources (iron, vanadium *etc.*) and, most of all, colonization.

And one of the main issues here is, again, propulsion. Sending people into space, on a trip that lasts for months, with the chemically-propelled vehicles currently in use, is not really efficient, let’s admit!

Fortunately, there are solutions. Ion thrusters, for instance, work by heating an inert gas (usually xenon) using microwaves, until electrons leave their orbits around the atoms, forming ionized plasma, that can be rapidly ejected using electrodes. Such engines were already used by NASA (NSTAR and NEXT projects). They work exclusively outside the atmosphere and allow groundbreaking accelerations, but are more suitable for the small-sized craft.

The main solution to efficient interplanetary transport is VASIMR (*Variable Specific Impulse Magnetoplasma Rocket*), an idea belonging to a former astronaut, Frank Chang Diaz. Its principle is similar but using instead electromagnetic fields for plasma ejection. Such engines are more durable and allow for transporting larger payloads. There are some drawbacks, including relatively low efficiency and issues with purging excess heat. For these reasons (and also political-bureaucratic ones), it never went past the laboratory phase. However, such a technology would allow travelling to Mars in just 39 days, instead of over half a year [3, 4]!

Either way, perspectives look promising enough that private companies, like SpaceX, began planning future Martian settlements [5].

Of course, the first colonies will probably be small mining and industrial settlements. Although many of you have in mind the classic space city under a transparent dome, that was made so popular by SF literature and cinematography, it is more likely for the first colonists to go underground.

Due to the intense volcanic activity in the planet's past, we have enough space at our disposal. We are talking about lava tubes, formed by differential cooling of lava flows: outer layers cool fast, turning into solid rock, while the interior keeps flowing away. We can find such formations on our planet, too, on the Moon and, maybe, on other planets.

Some are really huge: on Mars, such tubes were found to span 250 m in width (it seems a lot, but on the Moon, equivalent structures can be more than 1 km wide, being able to host entire cities the size of Philadelphia!). Their advantage is that they provide constant temperature conditions and radiation shielding (Fig. **4.2**) [6].

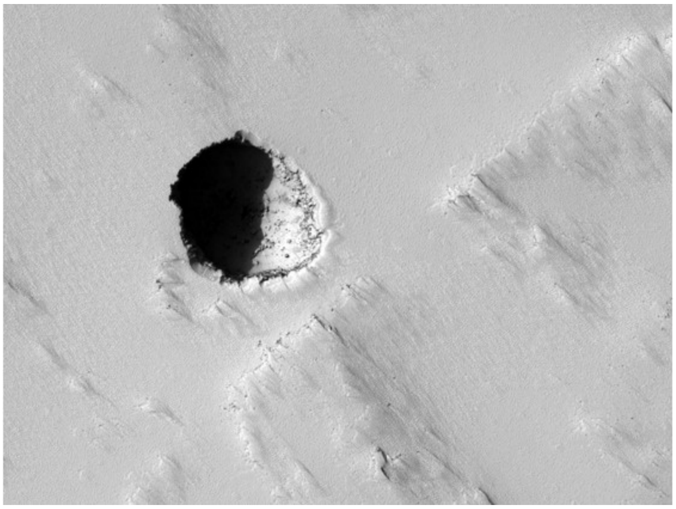

Fig. (4.2). The entry to a Martian lava tube [7].

Either way, the final goal is not to stay forever in such underground bases. We can do more: we can completely alter the Martian environment, in order to make it more earthlike. We can create an atmosphere that allows us to breathe, live and work under the Martian sky, without any space suit or breathing device. We can seed life on the Red Planet and turn this world into a new home.

We really can do it, and we even have the necessary technology to initiate the process called "terraformation".

4.1. THE MAKING OF EARTH

Terraformation (literally, "Earth-shaping") is a concept that initially appeared in science-fiction literature, in 1942, its creator being the novelist Jack Williamson. From SF, it passed into papers written by visionary scientists and today, it is a part of our mainstream language. Whereas once it was considered an extremely futuristic and marginal concept, nowadays we might hear it in the communicates of some public government institutions.

Martyn Fogg defined terraformation as "*a process of planetary engineering, specifically directed at enhancing the capacity of an extraterrestrial planetary environment to support life; the ultimate achievement in terraforming would be to create an open planetary ecosystem emulating all the functions of the biosphere of Earth, one that would be fully habitable for human beings*" [8].

First, let's see the conditions necessary to support life in general and human life in particular.

Even though any author wants his book to be read in one breath, it is much more likely that your main activity while reading this paragraph is actually breathing. All living organisms breathe, and most of them breathe oxygen. Experiments have shown that human organism can withstand atmospheric pressures starting at 50 kPa (half of Earth's atmospheric pressure at sea level) and up to 500 kPa (5 atmospheres), without health impacts. As for the composition, the partial pressures of each gas are more relevant than percentages. This is because pressure determines pulmonary absorption rate.

On Earth, the proportion of atmospheric oxygen (around 21 kPa) happens to be close to the maximum tolerable, above which toxicity occurs and, at over 30 kPa, living tissues tend to burn. The minimum tolerable is 13 kPa. However, we can "play" a bit with buffer gas concentration. It is strictly necessary in order to prevent the destructive oxidation of tissues. Although there are several inert gases that can be used, the most easily available and usable is nitrogen (the buffer gas here, on Earth). Its acceptable pressure can range anywhere between 30-475 kPa.

Yet, we cannot really "tamper" with carbon dioxide concentration. While insects and other invertebrates can withstand 5-10 kPa and plants even prefer higher concentrations than in the terrestrial atmosphere, this gas becomes highly toxic to humans at about 1 kPa. Obviously, micro-organisms have much lower requirements for their respiration and photosynthesis (see Table **4.1**). Actually, if it were only for the atmosphere issue, the Martian surface would already be habitable for them [9]!

Table 4.1. Minimal and maximal limits of habitability [2, 9].

Group of Organisms	Parameter	Limits	Observations
Micro-organisms and plants	Total atmospheric pressure	> 1 kPa (10 mbar)	Total gases + water vapor
	CO_2	> 0.015 kPa (0.15 mbar)	Minimal limit for photosynthesis
	N_2	0.1-1 kPa (1-10 mbar)	For nitrogen fixation
	O_2	> 0.1 kPa (1 mbar)	Respiration

(Table 4.1) cont.....

Group of Organisms	Parameter	Limits	Observations
Humans	Total atmospheric pressure	50-500 kPa (500-5,000 mbar)	Hypoxia/narcosis and embolism
	CO_2	< 1 kPa (10 mbar)	Toxicity
	N_2	> 30 kPa (300 mbar)	Buffer gas
	O_2	13-30 kPa (130-300 mbar)	Hypoxia/ flammability
General	Average temperature	0-30°C	15°C on Earth

There are still other limiting factors. One is temperature. An environment with constantly negative temperatures prevents photosynthesis and just about any other metabolic process, making the flow of liquid water impossible. Liquid water itself is a limiting factor, and it is estimated that the equivalent of a 500 m water layer above the Martian surface (obviously, distributed according to local landforms) would be necessary.

Furthermore, there is the need to shield against cosmic and ultraviolet radiation (Mars lacks an ozone layer) and remove damaging peroxides from the upper regolith [2].

The good news is that all these objectives are correlated. A higher temperature would release gases from the regolith, polar caps *etc.*, supporting the atmospheric building, and a progressively thicker atmosphere would lead to an increase in average temperature. Together, all these would allow liquid water to exist and a global hydrological circuit to start.

Water would wash the regolith, eliminating peroxides and releasing a small amount of oxygen. As for the ozone layer, there are two alternative pathways: it can form, just like on Earth, by reacting oxygen with ultraviolet light, but there is always the option of CO_2 photodissociation, in a thick atmosphere dominated by this gas.

And, of course, humans (like many other creatures) also need oxygen and food. For both requirements, there is a single reasonable solution: photosynthesis (with 43% of the incident light reaching Earth and a similar daylight cycle, the Martian environment is really suitable for this process). Thus, before accomplishing the actual terraformation, we need to change the planet into a state that allows hosting life forms such as microalgae, lichens and plants.

The planetary engineering process that allows installing a self-sustaining biosphere (no matter how limited or small is called, by specialists, *ecosynthesis* or *ecopoiesis*, meaning "creating a home/living environment” and it is the first of the two stages of terraformation (note that, even though we mention two stages, they are not entirely successive; for a higher efficiency and speed of the process, the first life forms should be introduced the moment that environmental conditions allow it!) [10 - 12].

And here, we need to address the issue of resources. More precisely, estimating the actual inventory of volatiles available for atmospheric building found on Mars.

Up until recently, due to a lack of precise data, estimates of CO_2 reserves were quite variate (the equivalent of 1-100 kPa, or, if you prefer, 10-1,000 mbar – since scientists were kind enough to create several units of measurement for pressure; note that the low gravity on Mars translates into an amount of gases three times larger than on Earth that is needed to reach the same pressure), but the consensus was somewhere between 30-60 kPa [12, 13].

Polar caps, especially the southern one, were thought to be among the main deposits, with somewhere around 5-10 kPa [2]. It was a real disappointment when scientific data proved that this cap, like its northern counterpart, is mostly made up of water ice, with a rather tiny percentage of carbonic ice. Although water is extremely valuable by itself, it is of little use for building an atmosphere, because it needs high temperatures to be evaporated.

Anyway, no terraforming scenario was mainly based on polar reserves, but on other ones, likely found in ice lenses and crystals found in the regolith of circumpolar regions and in carbonate deposits. At over 50 kPa, the atmospheric pressure would be acceptable, and with a composition dominated by CO_2 (a greenhouse gas!), the planet would soon get warmer.

In 2018, an article published by Bruce Jakosky and Christopher Edwards, two researchers involved in NASA’s MAVEN (*Mars Atmosphere and Volatile Evolution*) mission, seems to have made all these calculations obsolete. According to them, only 1.4 kPa could be sublimated from the polar caps and no more than 15 kPa (with a minimum around 0) from clathrate deposits (basically, bubbles of CO_2 trapped in ordinary ice). An additional 4 kPa might be adsorbed onto regolith grains down to 100 m depth.

What remains is only carbonate-rich rocks. Releasing CO_2 from carbonates can be accomplished by heating them at about 300°C. Analyzing strictly the rugged area called Nili Fossae (the largest contiguous carbonate deposit known and which is also easily accessible from the surface; (Fig. **4.3**), authors came up with three scenarios, depending on the actual area and depth of the deposit, starting from the equivalent of 0,025 kPa and up to 15 kPa. Their conclusion is that, by using currently available technical means, we could not accomplish more than increasing three times the current pressure, or, in the best-case scenario, reaching around 5 kPa. Thus, terraforming would be difficult to impossible, at least for now, which does not mean that terraforming advocates were discouraged [14].

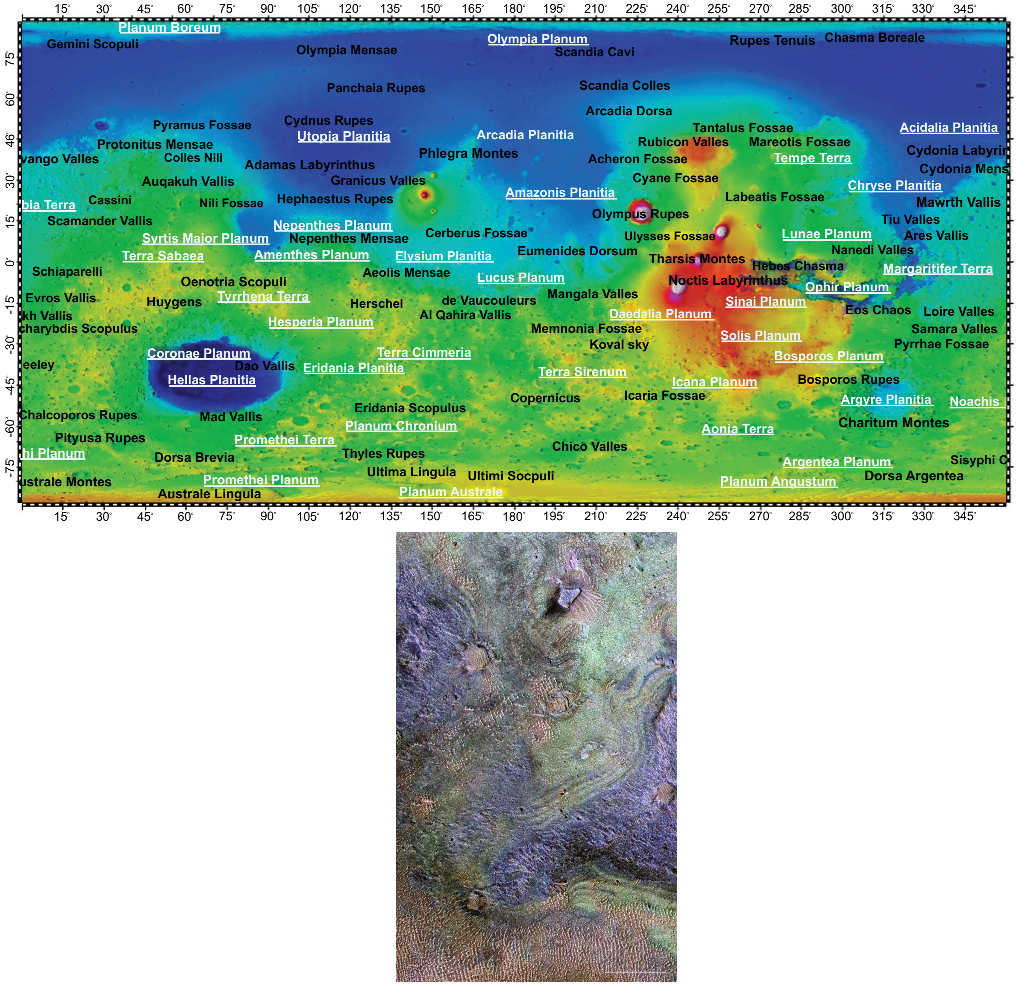

Fig. (4.3). Topographic map of Mars [15] and Nili Fossae: the most compact carbonate deposit known [14].

We are obviously talking about Elon Musk, supported by Christopher McKay and Robert Zubrin (authors of several papers in this field and, somehow, the "fathers" of terraforming through positive feedback concept, as we will find out below).

Their arguments are simple. First, while Nili Fossae is the most compact carbonate-rich area, it is definitely not the only such deposit on Mars. Second, the loss rate of the primordial Martian atmosphere (by solar wind erosion, Mars lacking a magnetosphere), estimated by Jakosky and Edwards, at over 75%, is highly disputable [15].

Even more important than that, critics question the estimated initial atmospheric pressure of 50 kPa. This is because paleohydrological data supplied by orbiter probes (meaning the distribution and flow directions of water in the planet's past) suggest a possible initial pressure of over 200 kPa (two times that of Earth's atmosphere). So, even at a 75% loss rate, the equivalent of 50 kPa would still remain trapped in the planet's crust, an amount that would make terraforming possible [16].

Whatever the truth is, the bottom line is there are solutions. Some are more subtle, while others are rather "brute", but they all can probably work even in the worst-case scenario, that of a few kPa of total degassable carbon dioxide.

In the first category, several methods involving the greenhouse effect were proposed. Briefly, heating the planetary surface by a few degrees or releasing an initial amount of CO_2 from the regolith leads to the thickening of the atmosphere and, through the greenhouse effect, supplemental warming. This extra heat, in turn, causes new amounts of CO_2 to sublimate and so on. Scientists call this phenomenon a "*positive feedback*", and such a "loop" would finally lead to an environment similar to the terrestrial one (except for the oxygen).

According to some estimates, an extra 4-5°C could cause the degassing of most CO_2 reserves [13] from the polar caps, while a 25°C increase would release massive amounts from the regolith, ensuring the self-amplification effect that, in turn, would lead to a complete ecosynthesis. This, of course, is in the optimistic scenario involving several tens of kPa of gas reserves in the regolith [9].

The most obvious way to do it is by detonating some nuclear bombs in strategic, volatile-rich areas. With caution, of course, in order to avoid excessively irradiating our future new home. This is the idea behind SpaceX's *Nuke Mars* advertising campaign [17].

And, yet, there is no need for a massive bombing operation. An idea would be detonating a few such devices around the southern ice cap. According to some calculations, four warheads, one megaton each, detonated at 100 m depth into the regolith, would be enough to raise enormous dust clouds, that would cover extended areas of the ice cap.

This would lower the albedo, meaning the reflectance, of the ice. Obviously, a darker object tends to be easier to heat due to the increased absorption of sunrays.

Carbon dioxide would start sublimating, "thickening” Martian atmosphere and creating the greenhouse effect [18].

Of course, there is always the question of whether there is enough CO_2 in the ice cap to trigger the feedback loop – and very likely, there is not. Yet, the thermonuclear approach has its advantages and can be used to release gases from other sites, including compact carbonate and nitrate deposits. Thus the idea is worth trying, keeping in mind the long-term effects of residual radioactivity [19].

“Classic” ecosynthesis scenarios, however, tend to use less violent methods, mainly heating the planet using orbital mirrors or industrial greenhouse gases.

As for the mirrors, we are talking about reenacting, at a much larger scale, the *Znamya* Project (see Subchapter **2.1**). For the system to work, these mirrors should have a diameter of at least 125-200 km, in order to raise the temperature by 5°C. When building such megastructures, we need to carefully balance gravitational pull and solar wind pressure.

Calculations show that an altitude of 214,000 km and a precise positioning towards the southern ice cap would be necessary (Fig. **4.4**). Of course, such a structure would be difficult to assemble, but not impossible. Despite the impressive size, some available building materials keep the whole mass between moderate limits. For instance, a mirror mostly built of aluminium would "only” weigh some 200,000 tons (the weight of a large oil tanker). A modular design would allow the assembling of the reflector directly into orbit [8, 20].

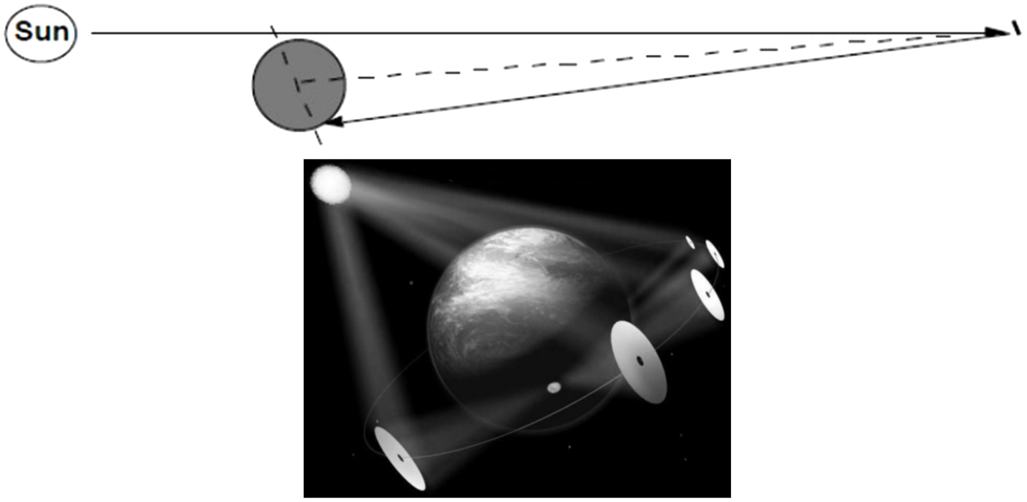

Fig. (4.4). Orbital mirrors: static equilibrium mirror [20] and polar orbit mirror [13].

An even more accessible solution would be a "swarm" of smaller-sized reflectors. A ring made up of such satellites, distributed on a stable, heliosynchronous, displaced polar orbit, would have the same cumulative effect (Fig. **4.4**) [13].

There are different variations of the concept. For instance, instead of placing mirrors into orbit, we could build them directly on one of the planet's natural satellites. Around Mars are two bodies, Deimos and Phobos, more likely two asteroids captured at one point by the planet's gravity (they have little over 12, respectively 22 km in diameter) than true moons.

Phobos, the fastest of them (8-hour revolution period) has a descending orbit and, in some 50 million years from now, it will crash on the planet's surface. Creating an array of independently moving mirrors, focused on a single spot and, maybe, moving the moon into a polar orbit (using nuclear blasts or NERVA thrusters), could solve part of the problem [21].

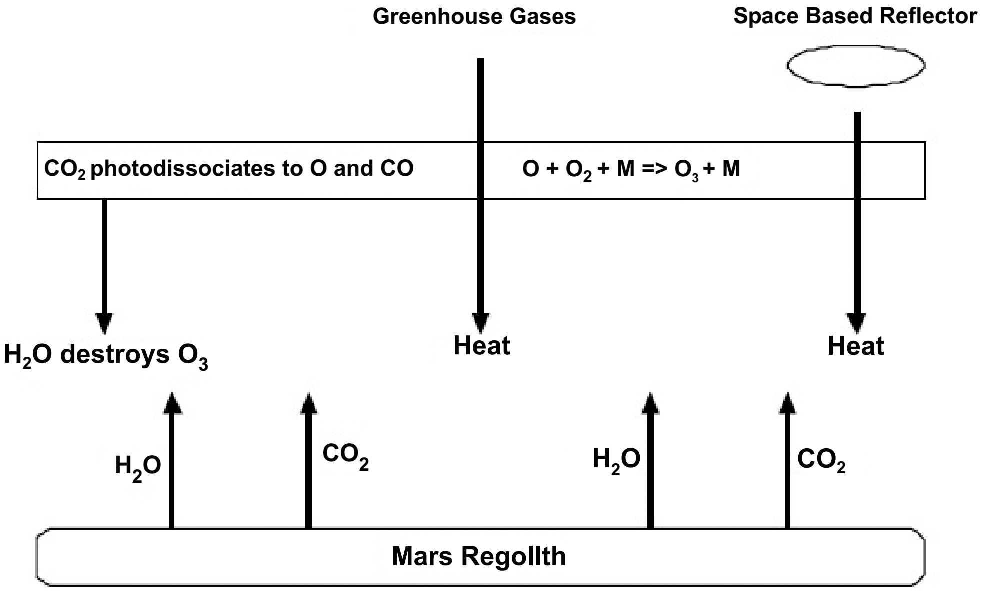

Fig. (4.5). Ecosynthesis through positive feedback, using orbital mirrors and greenhouse gases [11].

Another option at our disposal is that imagined by Paul Birch: the orbital mirror (much larger – 10,000 km – in his vision, but the solution could be adapted for moderate-size reflectors) would work together with an aerial lens, maintained at around 400 km above the ground. Thus, light would not just be reflected, but also focused in a narrow beam. If you have ever played with a magnifying glass under bright sunlight, you can imagine what the consequences: the concentrated light beam would "dig" deep into the regolith, degassing much larger amounts of CO2 are [22].

A classic solution, proposed by several authors within the last decades, is using greenhouse gases. And this is not about the "mild" CO_2, or water vapor, not even more potent compounds, like methane or ammonia (with an extremely short lifespan under continuous ultraviolet showering), but about much more effective and hardy industrial products.

We are talking about halogenated hydrocarbons belonging to a class called perfluorocarbons (PFCs), similar to the much-detested chlorofluorocarbons (CFCs). CFCs are polluting chemicals, mostly byproducts of the refrigerant industry, chemical fire extinguishers and also the electronic industry. They are largely responsible for the "holes" in Earth's ozone layer, thus being banned or limited by laws.

CFCs are also very effective greenhouse gases, but the carbon-chlorine chemical bond is susceptible to 200-300 nm UV radiation, leading to a short lifespan of such chemicals in the unshielded Martian atmosphere. Carbon-fluorine bond, on the other hand, is more resistant [8].

PFCs are also potentially polluting compounds. They are used as solvents, refrigerants, anesthetics, in the aluminium industry, *etc.,* They do not deplete the ozone layer (anyway, it would not be a problem on Mars), but they are greenhouse gases. Strong ones: 5,000-12,000 times more potent than CO_2! Partial pressure of just 0.1 Pa (equivalent to 1/6,000 of the current, negligible Martian atmosphere) would raise the average temperature of the planet by 10°C!

These compounds can be produced industrially, *in situ*. We just need some carbon and fluorine. Carbon is available, in large amounts, in the atmosphere, while fluorine can be extracted from minerals such as fluorite (CaF_2), cyolite (Na_3AlF_6), sellaite (MgF_2), villiaumite (NaF) or lithium fluoride (LiF_2), that apparently also exist on Mars, even though the compactness of the deposits is still unclear.

Through chemical methods (reaction with sulfuric acid, also easy to produce *in situ*), hydrofluoric acid can be obtained. Reacting it with the CO^2 atmosphere produces tetrafluoromethane (CF^4), more complex compounds, like octafluoropropane (C^3F^8) obtained by electrolytic methods [23].

Simulations have shown that the most suitable greenhouse gases would be CF_4, C_2F_6 and C_3F_8, among the PFCs, to which sulfur hexafluoride (SF_6) can be added [24]. Of course, producing these gases is not easy. We are taking about 10-20 million tons of PFCs, relying on some mineral resources, whose distribution is little known and with an energy consumption of around 4,500 MW for an extra 10°C (3-4 times an average nuclear power plant; numbers double for each more 10°C) [20].

This does not mean we cannot do it, using automated or human-controlled industrial plants. After all, if *Homo sapiens* are not good at polluting, who is?

Another non-destructive method that would help a lot of terraformation involves using geothermal water. On the Martian surface, water cannot stay liquid for long. Things change dramatically as we go deeper into the crust. As mentioned above, we know that part of the initial hydrological network continues to exist deep below.

Areas of porous regolith allow groundwater basins to exist, at high temperatures and pressures. Calculations show that the upper limit of geothermal reserves should be somewhere between 1-3 km underground, maybe even less, in areas with recent volcanic activity.

Most of the regions located north of 40° latitude are of great interest, especially the lowland areas in the Northern Hemisphere (see Fig. **4.3**) [25].

Thermal water could be extracted using conventional methods, like mud drilling (water melted from the permafrost, plus fine regolith), with nuclear energy sources. With a little effort, we can drill even deeper than 3 km. At 6 km depths, water might reach 300°C temperatures!

So, how could we use geothermal resources? In countless ways! Besides obtaining cheap energy for the future local industry, water could be directed towards craters and other depressions. This would create lakes (covered by ice layers, of course), suitable for aquaculture, producing food or preparing micro- and macroorganisms to be released on the planet's surface, after ecosynthesis. Some sort of small-scale terraforming.

As mentioned above, 300°C is the temperature at which carbonates decompose. Directing overheated water though carbonate deposits would release large amounts of CO_2. The same is true for releasing nitrogen oxides from nitrate deposits (though higher temperatures would be needed, in this case).

Finally, neither creating artesian wells of low temperatures is useless. And not for aesthetic reasons but because water would be carrying various impurities, splattering them on large areas of ice caps, for instance, lowering their albedo and helping them melt [25].

Note that there are many other proposed options for reducing the albedo of ice caps, circumpolar regions and planetary surface, in general, including spreading fine regolith over the ice caps, covering circumpolar lands with vegetation (microalgae, lichens; a method rather impractical in the first stages of terraforming, since these organisms could not withstand cold, anoxia and radiation) or, in the worst case, controlled crashing of Phobos and/or Deimos (formed, mainly, of dark carbonaceous chondritic material) [21].

An alternative that is worth investigating is the chemical conversion of the current Martian atmosphere. This can be done through the Bosch reaction, between carbon dioxide and hydrogen, at high temperatures and, preferably, in the presence of metallic catalysts (ferric iron, nickel, cobalt):

$$CO_2 + 2\ H_2 \rightarrow C + 2\ H_2O$$

In order to convert the entire atmosphere, some 2.16×10^{15} kg of hydrogen are needed, which actually means $10.8\text{-}21.6\times10^{15}$ kg, considering the maximum efficiency of the reaction is around 10-20%. An enormous amount, isn’t it?

And now, just imagine a wave of hot hydrogen with a mass of over 7×10^{15} kg and a temperature above 10,000°C (the minimum temperature of the solar wind; the reaction occurs at just 530-730°C, but it is a good idea to compensate the lack of a catalyst, since ferric iron – Fe^{3+} – is quite rare in surficial regolith) hitting Mars at high speed! This is the ejecta resulting from Jupter’s helioformation, as we will see in the next chapter (Subchapter **5.1**).

There are many advantages. The reaction is exothermic, instantly heating the planet by 78°C (add another 16°C, if we also helioform Saturn), which would quickly melt part of the ice. Resulting water vapor is also valuable, as a greenhouse gas (even more than CO_2), while the carbon would sediment as dark graphite on the planet’s surface (4-5 kg/m^2), lowering its albedo. And we might not need more than a thermonuclear warhead for this (see Subchapter **5.1**) [26]!

Finally, another proposed method involves "importing” CO_2 from a place where this gas is really in excess: Venus. This planet has an extremely dense atmosphere, with a pressure of 9,200-9,300 kPa, of which more than 96% is carbon dioxide.

We already discussed in Chapter 3 about orbital rings and other methods of atmospheric "mining”. And this is because launching any kind of payload from Venus is even more problematic than from Earth, due to the extreme atmospheric density. Furthermore, the local environment is very destructive and would cause fast wear of any industrial plant on the surface. Instead, an orbital ring, directly assembled into orbit and connected to a hose/pipe that would suck atmospheric gas, is a relatively convenient solution.

After reaching orbit, CO_2 can be compressed into pellets of carbonic ice and launched. This can be done with automated electromagnetic mass drivers (railguns/coilguns), permanently aiming at Mars. Once the initial impulse is given, the pellets would move, slow but steady, towards their destination, eventually with secondary propulsion of rocket thrusters or "solar sails" (thin membranes, made of aluminium and polymers or carbon fiber, using solar wind for propulsion; they are already being tested) [27].

Despite its ease, the big problem with this method is a quantitative one. Just to double the current Martian atmosphere, 25×10^{15} kg CO_2 is necessary. If we want to do it in 100 years, by using, let's say, 1,000 mass drivers, this would mean that each such railgun should launch no less than 30,000 tons per hour (the equivalent of a large maritime vessel)! Or, if you prefer, the equivalent of one mining truck per minute! And doubling the atmosphere is not enough, we need an amount several tens of times larger.

That means that, although the idea is a good one, it can only be used along with other ecosynthesis techniques.

Still, especially if the hypothesis of scarce volatile resources on Mars proves right, import becomes the only option. To this, another problem should be added.

If estimates of carbon dioxide reserves are highly variable, we really do not know much about nitrogen reserves.

In the extremely likely scenario that the primordial Martian atmosphere had a high percentage of nitrogen (similar to the atmospheres on Earth or on early Venus) [28], there are two possibilities regarding its fate: erosion by solar wind or sequestration into the crust. Considering that the atmospheric escape rate is lower for nitrogen than for CO^2, the latter process was probably the dominant one.

While accumulation as ammonia pockets inside the regolith is less probable because this gas is unstable under local conditions (although ammonia emissions of unknown origin seem to have been detected by Mars Express probe [29]), things change for ammonium and nitrate salts.

Scientists assume that ammonium ions (NH^+) could be trapped in the structure of some phyllosilicates in the regolith [30]. Nitrates (NO_3^-) are quite rare in surficial layers of the terrestrial crust because they are easily soluble (thus, easy to wash away by water) and easy targets for microbial denitrification. On Earth, compact nitrate deposits are found, as a consequence, in arid regions, especially in the Atacama Desert. Their sources are mostly electric ones (lightning, but also electric discharges occurring during volcanic eruptions).

But Mars is a huge desert, with some past volcanic activity, with no water flows in recent history and no known microbial activity. All these suggest a high likelihood of local nitrate deposits [2].

And now we know they really exist! Curiosity rover detected nitric oxide during the pyrolysis of regolith samples taken from around the Gale Crater, a clear sign of nitrate presence. It seems that some Martian sediments contain 0.1-1% nitrates. Furthermore, nitrates could be globally widespread, with concentrations up to 0.03% being found in mobile sediments (those brought by wind from surrounding areas) [31].

These are really good news, even if we still do not know much about the actual distribution of nitrate deposits and their accessibility. We might be forced, at least during the initial stages of terraforming, to import nitrogen.

One of the available solutions that of mass drivers was discussed above, with its quantitative drawbacks. As a nitrogen source, Venus is clearly an option. Its atmosphere contains around 3.5% N_2, which, in this case, means a remarkable amount. Yet, it would be difficult to separate from the carbon dioxide forming the rest of the atmosphere, while local reserves will prove useful when terraforming Venus itself (though the amount of nitrogen present would still be excedentary).

Titan, on the other hand, Saturn’s largest moon, has plenty of advantages to offer. Its atmosphere weighs some 9×10^{18} kg, of which over 94% is molecular nitrogen (13% of it would be necessary to create from scratch an optimal atmosphere on Mars). Add the low gravity, just 13.8% of the terrestrial one, which really favors spacelaunch. Shipments could be made either by robotic spacecraft (practically, massive, self-propelled tanks), or, much easier, by ballistic means [21].

Still, there is also the "brute” version of volatile import: hijacking asteroids and controlled crashing them on Mars. We are talking mostly about "iceteroids” (asteroids made of ice) and comets. The most "wanted” chemical compound, in this case, is ammonia. Ammonia is a strong greenhouse gas and, at the same time, it decomposes photochemically, forming N_2.

An older proposal involves launching a mission towards the trans-Neptunian regions of the Solar System (the Kuiper Belt, for instance, where such objects are more likely to be found). An asteroid of 10 billion tons (it seems much, but it would be just 2.6 km long) onto which four 5,000 MW NERVA thrusters would be attached, with some gravity assist when flying over Saturn, could be easily brought to Mars. The fuel would obviously be part of the asteroid's mass.

40 such impacts would double the Martian atmosphere, or even more if directed to nitrate-rich regions on the planet [20].

You may already guess the drawbacks of this method. First, doubling the atmosphere is still a small step towards terraforming. Second, no known celestial body is made 100% of ammonia.

In meteorites found on Earth, coming from an ancient carbonaceous asteroid, about 1% NH_3 was found. Even if it is possible that the initial asteroid contained a larger amount, we cannot expect more than a few percent [32].

The same goes for comets. Ammonia makes up no more than 1.5% of the Halley's Comet nucleus [33], while other have percentages below 1% [34].

There is, of course, the optimistic scenario that somewhere in the Kuiper Belt, or even in the vast assemblages of satellites of gas giants, there are ammonia-rich bodies (or, at least, rich in carbon dioxide, methane and other volatile resources). But even a 3 km asteroid, with 30% ammonia, would only add some 6.4×10^{12} kg of N_2 to the local atmosphere [23].

Thus, iceteroids can be useful only when combined with other methods.

There is, however, some good news. Since nitrates are likely to be present in the regolith (see above), we could simply let bacteria take care of the nitrogen issue. The process is called denitrification and is a part of the natural nitrogen cycle on Earth. Many bacteria can convert the NO_3^- ion to nitrites (NO_2^-) and then, to nitrogen oxides and, finally, to N_2. This process can be rather fast and, according to specialists, it could release anywhere between 6 and 30 kPa of nitrogen within 2-3 centuries [35].

On our planet, denitrifying micro-organisms are extremely widespread in soils, water, sediments *etc.,* The most numerous belong to the genera *Pseudomonas* (especially *P. denitrificans*, *P. perfectomarinus*, *P. aeruginosa*) and *Alcaligenes*, but also *Thiobacillus denitrificans* or species of *Magnetospirillum* (the latter can also withstand otherwise toxic concentrations of iron; it simply stores it in some magnetic organelles – magnetosomes) [36, 37].

A study conducted on *Pseudomonas aeruginosa* has proven that it can grow on Mars "soil" simulant, at over 65% CO_2 concentrations, without significant effects on denitrification efficiency [38].

Note that denitrification is only possible in a more advanced stage of ecosynthesis, one in which temperature and radiation levels reach reasonable limits and liquid water can exist (Table **4.1**)!

The most "violent" and radical method, however, is the one put forward by Orme and Ness, being effective even if local volatile resources are scarce. It involves a controlled impact with a rocky/metallic asteroid.

The authors use, as a model, the impact responsible for creating the Argyre basin (1,800 km in diameter). Shockwaves produced by the impact and partial destruction of the lithosphere could be the ones that created the Tharsis mountain range, the enormous Olympus Mons volcano and even the Valles Marineris canyon system (Fig. **4.3**).

The idea is to direct a massive asteroid towards one of the planet's poles. The optimal target would be the North Pole, and more precisely, Chasma Boreale, a huge fault line in the ice cap, since melted water would easily fill the lowlands in the Northern Hemisphere. Effects would be multiple: an instantaneous volatilisation of some water amounts, the release of carbon dioxide and nitrogen oxides from local deposits, melting other amounts of water and also triggering volcanic eruptions.

We are talking about eruptions produced by shockwaves in neighboring areas, but also by an eventual "antipodal volcanism" shockwaves are also transmitted through the planet's core, triggering eruptions in the opposite spot, meaning the South Pole (thus, melting/evaporating other amounts of water). And new eruptions bring new gas emissions, this time directly from the magma.

The asteroid responsible for the Argyre Crater seems to have had 900 km in diameter, but a smaller one could be enough for us. Obviously, maneuvering such an object is extremely difficult due to the enormous mass involved, but not impossible. NERVA rockets or mass drivers are the likely solutions. The alternative to moving asteroids hundreds of kilometers long is using swarms of smaller instead, but still rocky/metallic ones.

Briefly, despite technical issues, this method seems extremely appealing, providing access to deep volatile reserves. Authors estimate the duration of the entire ecosynthesis process to be just 50 years [39]!

To accomplish this, besides the methods already mentioned for deviating asteroids, there is also the option of using gravity assist. It is the concept used for accelerating, decelerating or altering the trajectory of spacecraft by close encounters with the gravitational fields of certain planets.

The same method was proposed for altering the orbit of celestial bodies, through regular passages made periodically by an intermediate-sized object (in this case, a smaller asteroid) [40], but we will find out more in the following chapter. One version of the process is gravity-powered traction – a spacecraft or, in this case, a small asteroid, diverted through "classic" means, would orbit around the target-body, slowly deviating its trajectory by its own gravity [41].

Finally, to end this overview of the resources necessary to ecosynthesis, we cannot forget about water. It is considered that a biosphere similar to the terrestrial one needs a minimal amount equivalent to a 70 m layer (optimally, more that 500 m), obviously distributed according to local landforms. For years, we have known that there are significant water reserves in polar caps, other compact ice deposits, permafrost and diffuse ice crystals in the regolith and groundwater. A total of anywhere between 6-1,000 m, but very likely more than 500 m [2].

Recent data are even more promising from this point of view, especially after we discovered that most ice caps are formed from frozen water. Thus, it is estimated that just the first upper meter of the Martian crust harbors the equivalent of 14 cm of water (meaning 14%). Ice caps contain 30 m of water, while total reserves are estimated to be around 500 m, which is exactly the optimum value for terraformation [42].

You will surely ask which of the proposed ecosynthesis methods should be applied. The answer is simple: ALL OF THEM! As you already saw, each one has its limitations and, in the very likely case of a low volatile inventory, nuclear blasts, orbital mirrors, geothermal wells, atmospheric conversion, volatile importation and controlled impacts will all prove useful to complete the task in a reasonable time.

4.2. THE MAKING OF HEAVENS

By applying the measures mentioned above, it is possible that, within a century or even less, Mars would look entirely different. Atmospheric pressure would rise, creating a thicker and thicker atmosphere, formed of N_2 and CO_2 and also having a protective ozone layer.

Average temperatures would steadily grow, up to 0°C and then above this value. Ice would melt, filling seas and lakes and, in time, evaporation would lead to clouds, rain and flowing watercourses. Briefly, the Red Planet would begin looking more and more like that in Fig. (**4.6**).

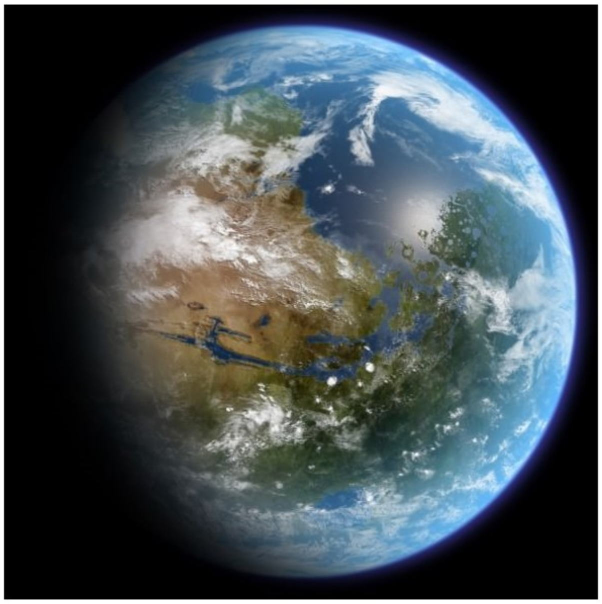

Fig. (4.6). A hypothetical image of a terraformed Mars [43].

However, be aware: there is still much more work to do! More precisely, there is the phase that some name *caeliformation* (literally, "making the sky”), altering the atmosphere to reach the parameters found on Earth [44].

And the main feature of our atmosphere is the presence, in large amounts, of oxygen. This is what makes it breathable and allows us, humans, to live under the open sky.

Currently, no other celestial body with such a concentration of atmospheric oxygen exists. And this is because, in nature, there seems to be a single efficient way to produce this gas: photosynthesis. Photosynthesis is a process characteristic to certain life forms and, due to its rather low efficiency (0.033 g CO_2 converted per cm^2 per year), converting the entire Martian atmosphere should take much more time than the initial ecosynthesis phase. We are talking about millennia [9]!

This means that we should hurry up and introduce life forms, mainly photoautotrophic ones, as soon as environmental conditions become acceptable, concerning temperature and atmospheric pressure levels (with temperatures above freezing point, in upper regolith layers, at least during the warm season). Even more, triggering a hydrological cycle on Mars and "washing” the regolith could release somewhere around 0.2 kPa of molecular oxygen from the peroxides contained in surficial layers. Too little for humans and animals, but enough for micro-organisms (see also Table **1.1**) [35].

Let's see the roles and qualities these pioneer organisms should have!

The first task was already discussed: converting, through photosynthesis, atmospheric CO_2 into O_2. On Earth, among the hardiest autotrophic organisms are cyanobacteria (once they were improperly called "blue-green algae", but they are actually a group of solitary or colonial bacteria, with a photosynthetic mechanism similar to that in the plant world) and unicellular green algae (Phylum Chlorophyta, classes Chlorophyceae and Trebouxiophyceae).

A connex function is that of producing biomass and, through death and decay, the organic component indispensable to creating soil.

Then, there is the release of volatiles and participation in the atmospheric building. Some micro-organisms are able to dissolve carbonates and release CO_2. Others are denitrifiers, producing N_2 out of nitrates. Finally, some can produce greenhouse gases, like ammonia and methane.

And, of course, there are those micro-organisms whose assistance is indispensable to all the processes mentioned above. Nitrogen-fixing bacteria turn atmospheric N_2 into ammonia ions, easily accessible to all photosynthesizing organisms and are essential to the nitrogen cycle in nature. Decomposers, on the other hand, meaning saprophytic heterotrophic bacteria, release organic compounds from dead life forms, being necessary to the natural carbon cycle and soil formation.

Finally, another important function is lowering the planetary albedo by covering surfaces as large as possible, thus favoring global warming [23].

In order to select the pioneer-organisms, we need to search for species as hardy as possible to the living conditions on Mars that are going through the first stages of terraforming.

The first important characteristic is psychrophilic, meaning resistance to cold. Specialists consider the average temperature from which life could thrive on a planet to be -10°C. But even at an average of 0°C or over, micro-organisms need to tolerate freezing periods (cold seasons, nights), by having mechanisms of cryptobiosis (slowing down their metabolism, producing spores/cysts, without long-term adverse effects).

Extreme drought, combined with the high salinity of the environment, tends to dehydrate cells, with lethal effects. Thus, we need micro-organisms that are adapted to desert and/or hypersaline environments, generally by accumulating in their cytoplasm large amounts of osmotically active (thus, hydrophilic) chemicals, like salts (KCl) or some organic compounds [23, 45].

It should be added to the tolerance to extremely low oxygen levels and, on the other hand, extremely high carbon dioxide levels. One of the effects of the latter is a very low pH of the external environment and, implicitly, of the intracellular one (so, we need acidophilic organisms).

Oligotrophy is another key characteristic. It means low demand for organic nutrients, which are obviously difficult to find on Mars. This problem is easy to solve for autotrophic organisms (including photosynthesizing ones), which prepare their own necessary organic compounds, from CO_2.

Resistance to radiation (ultraviolet, but also the residual radiation due to eventual nuclear blasts), is given by efficient DNA repair mechanisms, the presence of protective pigments (as in some Antarctic cyanobacteria), forming compact colonies, reflex avoidance of exposed areas or a hypo- or endolithic ecology (a preference towards living environments found under small pebbles or within the porosities of rocks).

Resistance to peroxides and other strong natural oxidants involves an intense synthesis of certain enzymes, specialized in quenching free radicals (like superoxide dismutase or catalase).

Finally, another necessary feature is tolerance to low atmospheric pressure, which generally affects DNA repair mechanisms [23].

Useful features can be improved in two ways: selection and genetic engineering (Fig. **4.7**).

There are, on Earth, extreme environments where micro-organisms of interest can be isolated and cultivated: circumpolar regions, deserts, high mountain areas *etc.*

Selection involves cultivating them under laboratory conditions more and more similar to those on Mars, a type of already common experiment. NASA and other research institutions created Martian regolith simulants, while the atmosphere can also be simulated in enclosed spaces with controlled gas composition and pressure (the so-called *Mars jars*). Low temperatures and UV radiation are even easier to simulate.

If you are interested, you can find online instructions to create your own simulated Mars environment, from easily available materials. Just follow this citation and the link attached [46]!

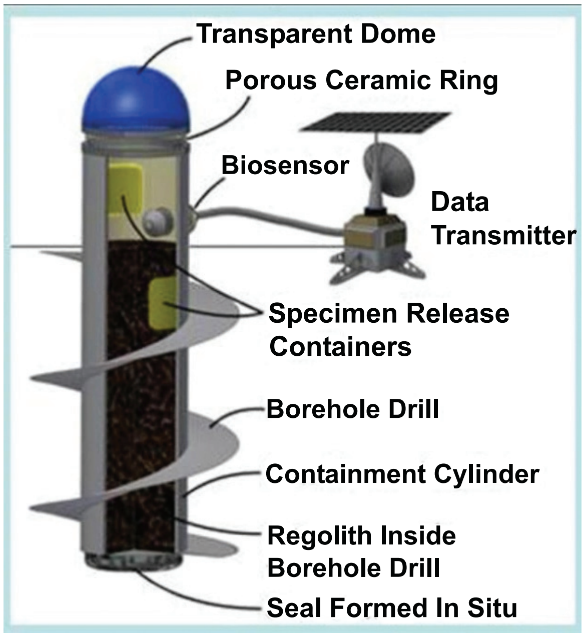

Fig. (4.7). Mars Ecopoiesis Test Bed: an automated device for seeding the Martian regolith with cyanobacteria [47].

Genetic engineering methods are also widely known and used nowadays. Briefly, genes of interest, inducing resistance to various environment factors or increased efficiency, can be transferred from one bacterial strain/species to another, for example.

At that time, Mars will probably host its own (semi) permanent human population. We are talking about miners, the personnel controlling perfluorocarbon-producing plants, researchers and even true colonists. Some of these human settlements will undoubtedly have the facilities needed to select and cultivate, on a larger and larger scale, necessary micro-organisms.

As shown above, groundwater can be used to create ponds and artificial lakes in any crater or depression on the planet. Below its ice crust, each of these lakes would provide an adequate environment for bacterial growth until the global thaw releases these organisms onto the bare surface.

Furthermore, maybe that "seeding” Mars with life could be done even at a small-scale level. *Mars Ecopoiesis Test Bed* is a proposed device that could be planted by robotic rovers. A cylinder featuring a drill can bury itself into the regolith (preferably, in areas with liquid water) and release cyanobacteria.

This way, one step at a time, small, autonomous microbial communities can develop all around Mars, waiting for the moment when they will be able to conquer the whole planet (Fig. **4.8**) [47].

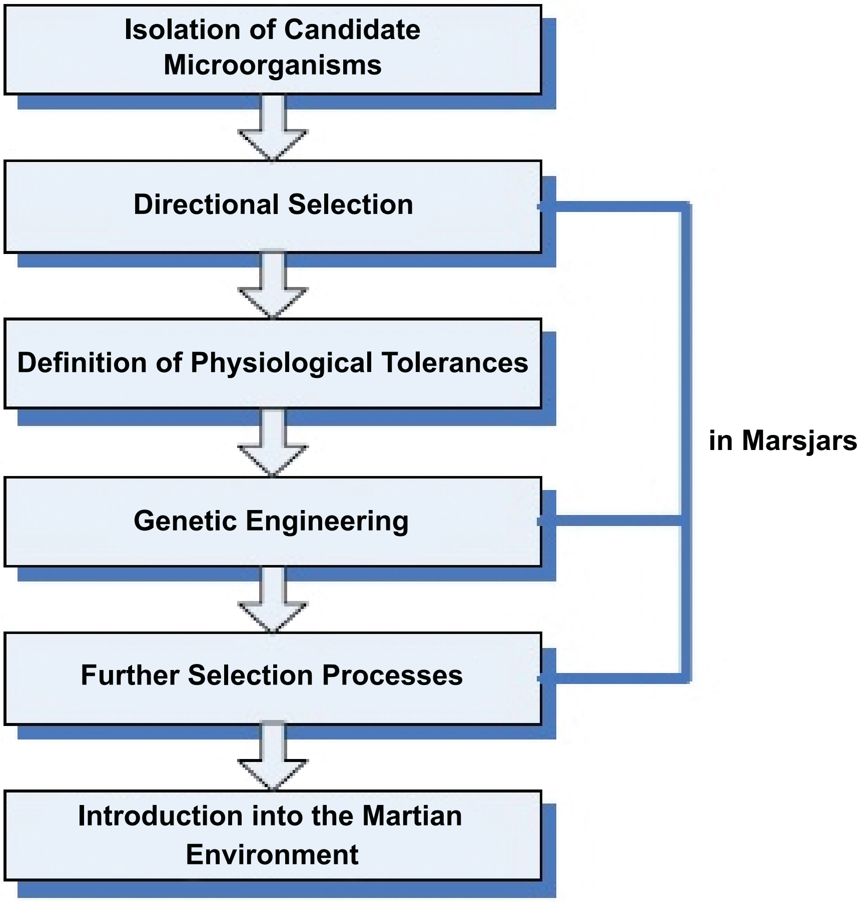
Isolation of Candidate Microorganisms
Directional Selection
Definition of Physiological Tolerances
Genetic Engineering
Further Selection Processes
Introduction into the Martian Environment
in Marsjars

Fig. (4.8). The general scheme for adapting micro-organisms to Martian environmental conditions, through selection and genetic engineering [23].

And now, let's see some of the protagonists of this early stage of Martian life!

The *Chroococcidiopsis* genus comprises several species of cyanobacteria considered "primitive". They perform photosynthesis, just like all their relatives, and many of the species are well-known for their ability to withstand extreme environmental conditions. They are common inhabitants of terrestrial deserts, tolerating extremely low or high temperatures, severe drought and high salinity (including excessive nitrate concentrations).

They are hypolithic, meaning they take shelter from ultraviolet radiation and extreme drought under translucent stones. The same strategy also works for avoiding cold (the hypolithic environment ensures a temperature up to 15°C higher than the atmospheric one). They are also anaerobic, so they do not need an initial oxygen amount.

C. caldariorum species, for instance, has Antarctic origins and withstands daily freezing periods. Finally, these cyanobacteria can survive with extremely little water (they can be wet once a year!), although dehydration certainly slows down their metabolism [23, 48].

Species belonging to *Matteia* genus (also cyanobacteria and also phototrophic) form filamentous colonies. They perform photosynthesis, have the ability to fix atmospheric nitrogen (thus, they do not need local reserves of nitrate or ammonium salts), and, even more, they have te ability to dissolve carbonates and can release CO_2 from the regolith [49].

Such bacteria were isolated from limestones (they are endolithic) from the Negev Desert (Israel), so they can also thrive in extremely arid conditions [50].

To these, we can add drought-resistant species of the genera *Anabaena* and *Plectonema*, and also a plethora of Antarctic cyanobacteria, extremely versatile, epi-, endo- or hypolithic, tolerant to anoxia, freezing, ultraviolet radiation and free radicals, having photoprotective pigments and efficient DNA repair mechanisms [35, 50].

These would be the pioneers of photosynthesis, the first organisms to consume CO_2, oxygenating the atmosphere and creating biomass wherever there is even a tiny amount of moisture (Fig. **4.9**).

Not just cyanobacteria can be useful, effective and hardy, but also algae. No, do not think of sea lettuce, but of rather microscopic green algal species (but also diatoms), that can grow in water and on any relatively moist substrate (see also Table **1.2**).

Species of *Chlamydomonas*, *Chlorella*, *Scenedesmu*s, and *Selenastrum* can withstand anaerobic and CO_2-rich environments. *Pyrobotrys* even grow exclusively on anaerobic soils! Under strict anaerobiosis, it and its relatives use alternative mechanisms to function: fermentation and, if anoxia persists, reducing carbon dioxide with hydrogen (previously produced by fermentation), to synthesize organic compounds [51].

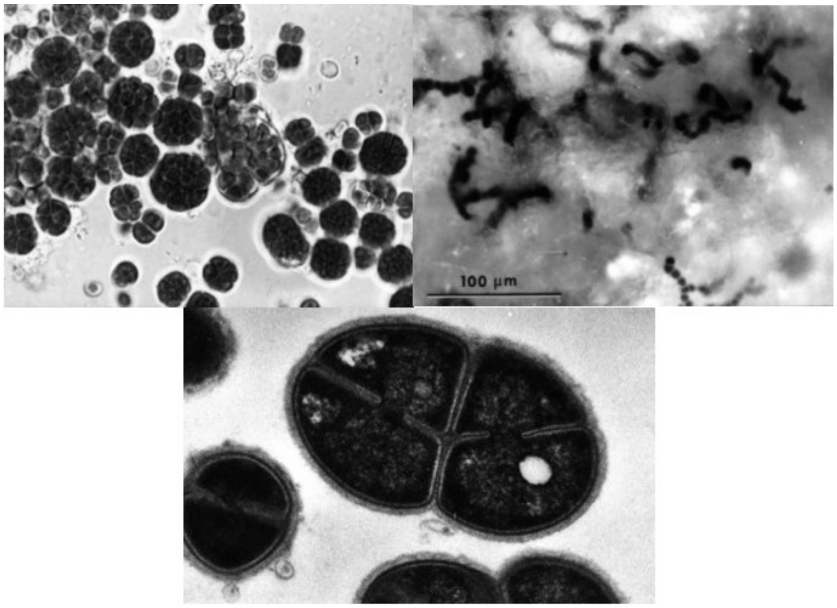

Fig. (4.9). Bacterial pioneers of Martian terraformation: *Chroococcidiopsis* sp., *Matteia* sp., *Deinococcus radiodurans* [51].

Hemichloris and *Trebouxia* (the latter found alone or in lichens) are able to thrive in the frozen valleys of the Antarctic. And photoprotective pigments allow some algae, such as *Micrasterias denticulata,* to tolerate high levels of UV radiation [52].

However, besides photosynthesis, the other important process to pursue is triggering a planetary nitrogen cycle (Fig. **4.10**).

On Mars, it would all start with the microbial denitrification of nitrate reserves. We have already discussed the abilities of some *Pseudomonas* species, but also of other chemoautotrophic bacteria, like *Thiobacillus denitrificans*.

Once N_2 is available in the atmosphere, it needs to reach all microbial ecosystems, supporting photosynthetic activity. The process is called microbial nitrogen fixation and leads to forming nitrogen nutrients – food for other organisms. Nitrogen-fixing bacteria are widespread in terrestrial soils and waters, as solitary or colonial organisms, or sometimes involved in various symbioses.

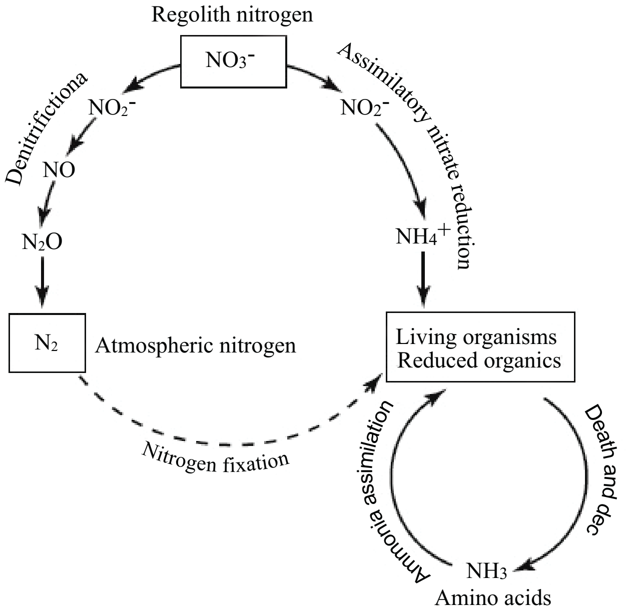

Fig. (4.10). The biogeochemical cycle of nitrogen on Mars [52].

Table 4.2. Micro-organisms (archaea, bacteria, green algae, diatoms, fungi) have valuable characteristics for the first stages of terraforming Mars [50].

Characteristic	Species and Groups of Species
Autotrophy: oxygenic photosynthesis	Cyanobacteria, algae
Autotrophy: chemosynthesis	*Nitrosomonas*, *Nitrobacter*, *Thiobacillus*, Methanogenic archaea
Psychrophila	*Pyramimonas*, *Fragilariopsis*, *Pseudo-nitzschia*, *Porosira*, *Entomoneis*, *Nitzschia*
Tolerance to high CO_2 concentrations	*Anabaena*, *Plectonema*, *Cyanidium*, *Nannochloris*
Tolerance to hypoxia	*Anabaena*, *Plectonema*, *Cyanidium*
Dissolving carbonates	*Matteia*, other cyanobacteria and algae
Denitrification	*Pseudomonas*, *Paracoccus*, *Streptomyces*
Nitrogen fixation	*Anabaena*, *Chroococcidiopsis*, *Cyanothece*, *Synechococcus*, *Trichodesmium*
Halophilia and drought tolerance	*Chroococcidiopsis*, *Halomonas*, *Klebsormidium*, *Oscillatoria*, *Phormidium*, endospore-producing bacteria, extreme-halophilic archaea
Resistance to ultraviolet and/or ionizing radiation	*Aspergillus*, *Bacillus*, *Chroococcidiopsis*, *Deinococcus*, *Mycobacterium*, *Rubrobacter*

(Table 4.2) cont.....

Characteristic	Species and Groups of Species
Low-pressure tolerance	*Aspergillus*, *Mycobacterium*, *Pseudomonas*, *Staphylococcus*, *Streptococcus*

It was found that some strains of *Azotobacter vinelandii* and *Azomonas agilis* can initiate nitrogen fixation at partial pressures as low as 0.5 kPa [50]. And some other nitrogen fixers, like *Rhizobium leguminosarum* (the endosymbiont in legume roots), can be genetically modified to tolerate a soil pH of just 4.4 [45].

Not to mention, of course, the remarkably valuable micro-organisms that are able to perform photosynthesis while also fixing the nitrogen they need (*Chroococcidiopsis* sp., *Anabaena* sp. *etc.*).

Besides these species, we should also mention polyextremophiles, organisms that tolerate a wide variety of environmental factors.

Maybe the most remarkable is *Deinococcus radiodurans*. A combination of protective pigments, antioxidizing enzymatic complexes, multiplication and compact packing of the genome and efficient mechanisms that isolate and repair altered DNA fragments allow this bacterium to withstand radiation doses that would instantly kill any other living being. *D. radiodurans* was isolated even from places like cans sterilized using gamma rays or from the cooling water of nuclear reactors.

It tolerates extreme drought and oxidizing agents, as well. Some of these relatives are able to withstand the high temperatures of hot springs. It is heterotrophic (although it only needs low amounts of organic material). Even if not really useful by itself, in the early phase of terraforming, it can function as a gene reservoir for enhancing the resistance of photosynthetic or denitrifying micro-organisms, through genetic engineering [23].

The aim of this microbial phase of terraforming is to establish an extensive and self-sustaining microbiota, to constitute the major biogeochemical cycles (see Fig. **4.11**) and to create suitable conditions (atmosphere, soil) for the next waves of more complex organisms.

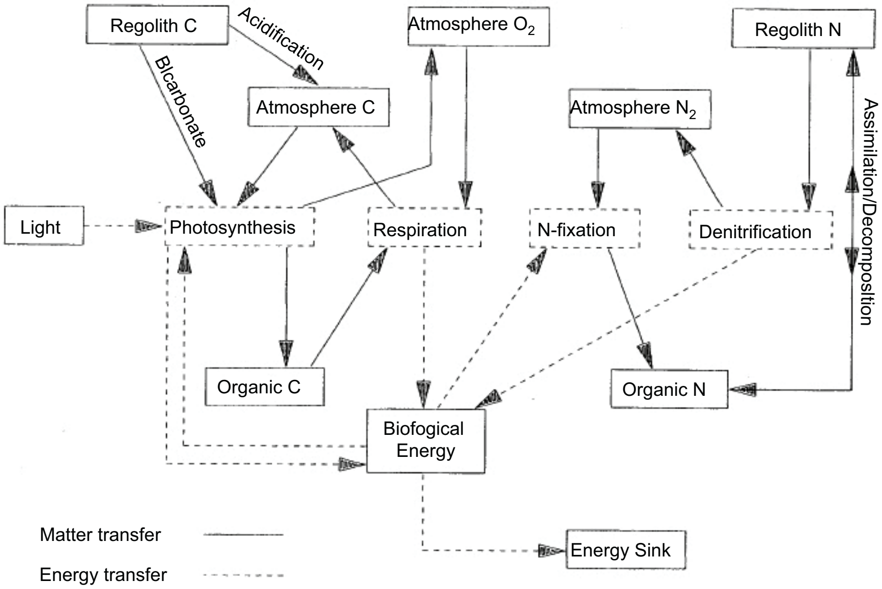

Fig. (4.11). The biogeochemical cycles of carbon, oxygen and nitrogen on Mars, are put together [53, 54].

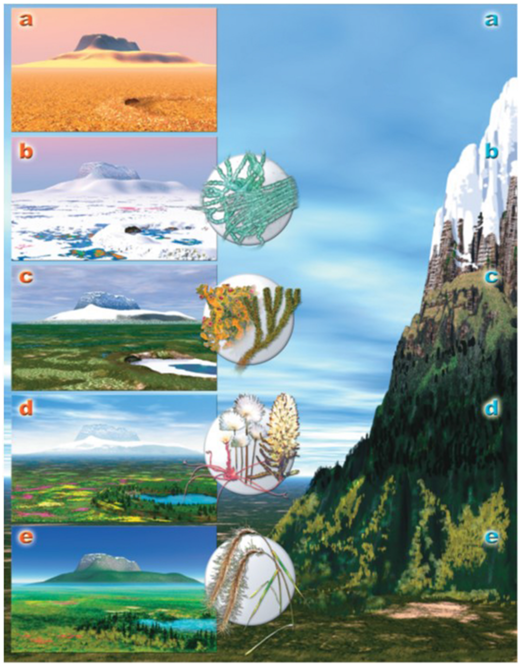

Fig. (4.12). Terraforming as ecological succession: (a) current, abiotic stage; (b) microbial, cyanobacteria-dominated "nival"/„polar” stage; (c) tundra stage, with lichens and mosses; (d) "boreal” stage, with tundras/cold steppes and incipient forests; (e) temperate stage, with steppes plus coniferous and deciduous forests [52].

According to specialists, the biological colonization of Mars (and other terraformable celestial bodies) would resemble the altitudinal and latitudinal ecological zonation on Earth (Fig. **4.12**).

Imagine a high mountain. Around its peak are permanently frozen barren lands, where only the hardiest micro-organisms dare to live. It is, more or less, the environment described above.

As we descend and the local climate gets warmer, there is a new form of vegetation: alpine tundra (or Arctic/Antarctic tundra, at high latitudes). And tundra primarily means lichens and mosses.

Lichens are symbiotic associations of fungi and microalgae and/or cyanobacteria. They have the disadvantage of slow growth rates but are photosynthesizing and can be extremely hardy.

Some lichens can withstand CO_2 partial pressures up to 0.2 kPa. It was found that some Antarctic species manage to photosynthesize even at -18°C ambient temperature, having mechanisms that prevent intracellular water from freezing. They are even able to resist temporary exposures to temperatures as low as -196°C!

Some are endolithic, thus avoiding direct exposure to UV radiation. Others can withstand impressive radiation doses (up to 5 times higher than those currently showering Mars), even while directly exposed, due to pigments like melanin and carotenoids. This is the case with *Cladonia rangiferina* (reindeer lichen), widespread in the Arctic tundra.

The organic acids they secrete dissolve rock, decisively contributing to the early stages of soil formation [52].

Bryophytes (mosses) are primitive plants and are no less hardy. One of their main qualities is their tolerance to hypoxia and elevated concentrations of CO_2. At normal terrestrial levels of carbon dioxide of 0.036 kPa, they tend to grow slowly. Things change, however, at higher levels.

Sphagnum fuscum, a peat moss, common in Arctic regions, has a much more intense metabolic activity at 0.9 kPa CO_2. *Grimmia antarctici*, a similarly widespread Arctic species, prefer 1-2 kPa. And for *Hypnum cupressiforme*, the optimal partial pressure of oxygen seems to be 3 kPa (meaning 3% of the atmosphere!).

Apparently, some polar and alpine species, such as *Andraea* sp., *Bryum argenteum* or *Ceratodon purpureus* have large enough amounts of flavonoid and carotenoid pigments to withstand UV radiation. There are even some (*Hylocomium splendens*) that find increased doses of radiation to be stimulating for their photosynthetic process.

One of the most important organisms for terraformation is peat moss (*Sphagnum* sp.). There are many species, some being extremely resistant to hostile environmental factors, as we saw. Peat bogs have the useful property of sequestering, under high moisture and acidity conditions, large amounts of carbon dioxide, a fact of major importance for caeliformation.

They are also effective at producing oxygen. It is estimated that only peat bogs could produce 2 kPa of oxygen, within a period of 700 years. Keep in mind that 13 kPa is the minimum needed for human breathing.

The requirements are a stable hydrological cycle (peat bogs only form in wet areas) and average temperatures above 7°C [35].

But let's not ignore aquatic ecosystems! On Earth, marine phytoplankton is the one regulating the O_2 and CO_2 content of the atmosphere. And aquatic environments have a big advantage: the presence of soluble ions like Br^-, Cl^-, Fe^{2+} and Mg^{2+}, and the depth of the water layer itself, providing protection against ultraviolet radiation. Cyanobacteria, diatoms or dinoflagellates, either psychrophile, acidophile or halophile, could be some of the most favored and efficient pioneers of terraforming [21].

In the same aquatic environments, we could also introduce the first vascular plants. Many species of monocotyledons living in ponds and swamps are well-adapted to hypoxia and elevated concentrations of CO_2. And this is because their seeds must germinate in the mud, where oxygen is scarce, while their underground organs (rhizomes, roots) must also withstand anoxic conditions. Among their adaptations are aeriferous tissues (with lacunes and channels for transporting air), starch as their main nutrient reserve (especially in seeds), fermentation mechanisms, resistance to cellular fluids acidification or antioxidizing complexes to resist the periods of transition from anoxia to normal oxygenic metabolism.

Among the most hypoxia-tolerant plants are *Carex misandra* and other species of *Carex* (sedge), *Iris pseudacorus* (water flag), *Eriophorum* sp. (cottongrass), *Juncus* sp. (rush), *Schoenoplectus americanus*, *S. lacustris* (club-rush), *Scirpus* sp. (club-rush), *Typha angustifolia*, *T. latifolia* (cattail). Add brackish water plants, like *Najas marina* or even marine ones, such as *Zostera marina*, and also dicotyledons, like the yellow water-lily (*Nuphar lutea*) [52].

As the atmosphere continues to warm and oxygenate, land-dwelling plants can also come in. It is considered that the minimum oxygen pressure needed is around 2-2.5 kPa (for more tolerant plants, like rice, *Oryza sativa*), but it varies from species to species. Corn (*Zea mays*) needs at least 6 kPa.

Among the most tolerant plants to periods of hypoxia/anoxia and also to low temperatures are some Arctic species, like *Cardamine nymani*, *Lycopodium selago*, *Luzula arctica*, *L. confusa*, *Poa alpina*, *Saxifraga caespitosa*, *S. foliosa* and *S. oppositifolia*.

An important issue here is reproduction. Pioneer species must not depend on insects for pollination. This is because insects cannot withstand partial oxygen pressures below 4 kPa.

Alternative means of reproduction include vegetative reproduction (basically, self-„cloning" through fragmentation of vegetative organs – bulbs, rhizomes, stolons, bulbils), apomixis (seed produced with no fecundation) or autogamy (self-pollination of flowers). We can add anemophilous pollination, that is, by the wind.

Among the Arctic autogamous species, or which do not need pollination at all, we can find species of the aforementioned *Saxifraga* genus, like *S. cernua*, *S. flagellaris*, *S. tricuspidata*, Arctic poppy (*Papaver radicatum*), Arctic dandelion (*Taraxacum arctogenum*) and moss campion (*Silene acaulis*) [35].

In time, conditions will even allow the planting forests. On Earth, temperatures above 3-7°C and altitudes below 4,000 m allow trees and shrubs to grow. Species like birch, willow, and alder, among deciduous trees, and larch, fir, spruce and various species of pine, among conifers, could begin populating the surface, beginning with sheltered valleys [2, 52].

Among animals, the first colonists will undoubtedly be invertebrates. Earthworms, for instance, are relatively tolerant to hypoxia and play a key role in soil loosening and oxygenation. We can add insects, as pollinators and bases for more complex trophic chains, in land environments, and crustaceans, in aquatic ones. Gradually, higher and higher-ranking consumers would be introduced on the planet [21].

In the end, at 13 kPa O_2 and below 1 kPa CO_2, Mars will be ready for *Homo sapiens*. A world where our descendants will be able to thrive under the open sky, farm the land and raise livestock.

How much will it take? The less optimistic specialists speak of millennia, maybe even somewhere around 100,000 years! Other researchers consider that, by using adequate management, at our current scientific and technological level, terraforming could be completed in just one millennium (Table **4.3**) [2, 52].

Table 4.3. Approximate temporal scale of terraforming Mars [52, 54].

Stage	Year	Dominant Organisms	N_2	O_2	CO_2
Prebiotic	Present – 100 years	-	0.27 mbar-increasing	-	<10 mbar-increasing
Microbial	100-300	Cyanobacteria, algae	<300 mbar	<2-4 mbar	>90 mbar
Briophytes	300-600	Lichens, mosses	300 mbar	2-20 mbar	Decreasing
Flowering plants	600-800	Anoxia-tolerant herbs	300 mbar	20-60 mbar	Decreasing
Boreal	800-900	Conifers	300 mbar	60-80 mbar	Decreasing
Temperate ecosystems	900-1000	Deciduous trees	300 mbar	80-over 120 mbar	<10 mbar

This is the reason we need to start the whole process as soon as possible!

4.3. MAINTENANCE WORKS

So, after a millennium, it is possible to see Mars becoming a sister-planet to Earth, with a breathable atmosphere, bodies of water, wild flora and fauna, crop fields and a flourishing civilization with billions of people.

Perhaps we will not be able to entirely recreate the terrestrial biosphere. It is not very likely that all the species and all ecosystem types will find their place on the new planet. Maybe we will not have tropical jungles, but the goal is to have a self-sustained and human-sustaining biosphere.

Mars would host a productive civilization, since the planet’s crust contains just about the same mineral resources as Earth’s (except, maybe, for hydrocarbon deposits, although there are chances to find these, too). Iron, titanium, vanadium, non-ferrous metals, will make the "Red Planet” a powerful industrial center. Deuterium is five times more abundant on Mars than on Earth, being a key resource for the future nuclear energy industry [53, 54].

Finally, low gravity would turn this planet into a much better launch base for travelling through the Solar System. It could even become a strategic hub for accessing the Main Asteroid Belt [55].

This does not mean that terraforming will simply come to an end. Unfortunately, there are some long-term problems that, at some point, will affect our Martian descendants.

First of all, Mars lacks a significant magnetosphere and this is not something to simply create from scratch. This is because the planetary magnetic field is created by the movements of the outer, fluid core of the celestial body.

Earth's magnetosphere is the one deflecting part of the high-energy particles coming from the Sun. We are talking about the solar wind protons diverted towards the poles, forming auroras. These protons can be more troublesome to electronic equipments than to life itself, especially considering that, at a pressure similar to the terrestrial one, the Martian atmosphere would have a mass 2.6 times higher (to compensate for gravity differences), thus being much more effective in shielding the surface from such particles [12].

The problem resides in the slow erosion of the upper atmosphere, which would lead to a deficit of atmospheric gases after millions of years. Meaning, probably, the same phenomenon that turned Mars into the arid world that it is now. Actually, the planet had a magnetosphere up until 4.2 billion years ago, after which the rotation of the planetary core slowed down and stopped (this probably led to atmosphere loss, in a period of around 500 million years). There are still magnetic fields in some areas of the crust, but they are 40 times weaker than the terrestrial one [56].

The good news is that there are solutions to this problem. Actually, no less than two solutions!

The first one is creating an artificial magnetosphere which would be based on the planetary surface. Actually, the solution was initially put forward for Earth, to supplement our protection in case of periodic magnetosphere fluctuations.

We are talking about an ensemble of 12 superconductive cables wrapped around the planet latitudinally, at regular intervals (including the Equator, of course). Do not think of huge-scale devices! These cables would have just 60 cm in diameter (36 cm being the actual superconductor), cooled with liquid nitrogen, require maximum energy of 12 GW (1% of the total output of the USA!) and would produce the equivalent of 10% of Earth's natural magnetic field (Fig. **4.13**).

More cables mean more magnetic intensity, although 11% of Earth's magnetosphere was calculated be enough to effectively shield Mars [57].

The second option, the one gaining ground lately, is the extraplanetary one. The "father" and main supporter of the idea is dr. James Green, director of NASA's Planetary Science Division.

Actually, it involves placing a strong electromagnet at the Lagrange L1 point (the gravitational equilibrium point between Mars and the Sun), at a distance of 1,084,000 km (320 times the planetary radius). This structure would permanently accompany Mars, deflecting the solar wind (Fig. **4.13**).

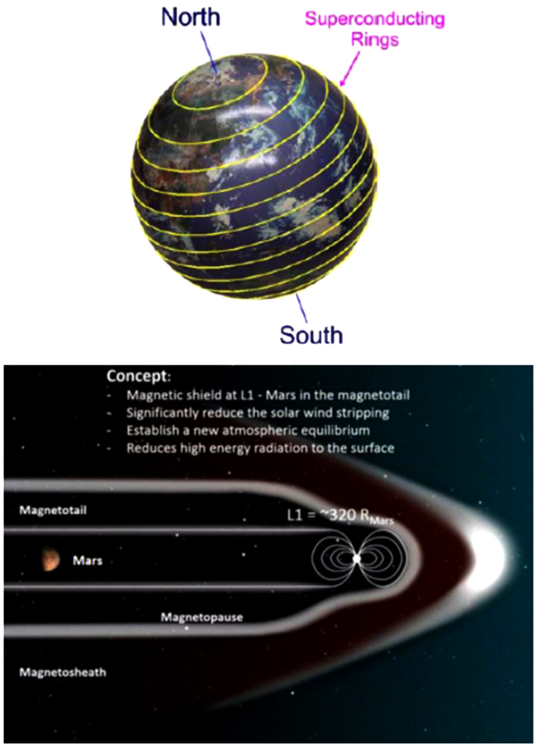
North
Superconducting Rings
South
Concept:
- Magnetic shield at L1 - Mars in the magnetotail
- Significantly reduce the solar wind stripping
- Establish a new atmospheric equilibrium
- Reduces high energy radiation to the surface
Magnetotail
L1 = ~320 R_{Mars}
Mars
Magnetopause
Magnetosheath

Fig. (4.13). Creating artificial magnetospheres using ground-based superconductive cables [57] or space-based electromagnets [56].

Such an electromagnet should generate a bipolar field, with a 1-2 tesla flux, which is already within our current technical capacities (there are experimental magnets yielding much stronger fluxes). According to the proponents, such a device would be a terraforming device by itself [58].

Other specialists did the necessary calculations. They show that such a device would require, as an energy source, a single 830 MW nuclear reactor, while the device itself would be a copper solenoid, doughnut-shaped, weighing 57 tons and having 3.5 m in diameter. The whole thing, including the reactor and other, connex devices, would not weigh more than 300 tons [59].

Still, atmospheric gases are not lost only due to solar wind. Another reason is the lack of tectonic activity. Carbon can gradually "sink" into the crust, as carbonate rocks or hydrocarbons. The same goes for phosporus and other key elements for life. On our planet, this is compensated by periodic volcanic emissions, due to tectonic phenomena. But on Mars, although there are traces of relatively recent volcanism, there is no plate tectonics.

Thus, some essential compounds, especially amounts of organic carbon, would be gradually lost to the crust, with no chance of resurfacing too soon. It is estimated that such a phenomenon could lead to serious problems within some 10 million years.

This is quite a long time, but it is always a good idea to find solutions as soon as possible. One idea is to continuously import volatile compounds. By slow disintegration (*aerobraking*) of these charges, the future Martians will be rather unhappy to have their planetary surface directly bombed with asteroids full of CO_2, ammonia *etc.*!

Another solution is to industrially extract and release these gases. For instance, annual production of 400 million tons of CO_2 would be enough to close the carbon cycle. It seems much, but, on Earth, we release over 20 billion tons yearly, just by burning fossil fuels.

In time, fossil fuels will also form on Mars. Until then, the equivalent would be the thermal decomposition of 750 m^3 of carbonates yearly. It is not difficult: it means the equivalent of 0.05% of the current mining activity on Earth, consuming 0.5% of the global energy output [60].

Other gases go upwards, due to low gravity. It is the case with hydrogen. Hydrogen is a light gas, due to its atomic and molecular structure, so that part of it tends to get lost to space. While the process is slow, in a very long time, Mars would begin lacking the main compound containing hydrogen: water.

There are some possible approaches to this problem, but one of the simplest and most logical ones involves solar wind. Yes, that is exactly the same solar wind wearing away the unprotected atmosphere.

The concept put forward by dr. Mark Culaj, from the Kosovo Space Exploration Agency, looks a lot like the extraplanetary magnetosphere generation system, but with a different size and direction.

A massive toroidal device, 20 km in diameter and weighing over 5,000 tons, would pe placed at the L1 point. The magnetic field would be oriented with its poles following the Sun-Mars axis, thus capturing and concentrating hydrogen ions. Besides extracting some useful hydrogen and helium isotopes (for nuclear-electric purposes), most of the hydrogen would be beamed to the Martian surface.

The total amount of hydrogen reaching ground would be 600 times higher than that in the solar wind, uniformly distributed onto the surface (the final diameter of the beam would be around 20.000 km). Hydrogen would not erode the atmosphere, because it would directly target the surface. On the contrary, it would compensate for the amounts lost due to low gravity.

Although massive, this solar wind trap could be used in combination with satellites that would further concentrate (through similar means) the hydrogen flux, in compact, hot beams. This way, it could become a terraforming instrument by itself, usable for other planets, too [61]!

Finally, there is the gravity issue. At 0.38 g, we cannot speak of weightlessness nor microgravity, but this is still low gravity. Although it might favor agricultural crops, allowing plants to grow taller, it is very likely to induce a deficitary development of bone and muscle tissue of human colonists.

However, this drawback can be easily corrected though physical exercise, medication and food supplements with bisphosphonates and parathyroid hormones, and even through periodic visits to Earth [23].

CONCLUSION

Terraforming Mars would be the key project of the next future. It is not easy to accomplish, requiring a sustained Global effort, but it will open the way for massive space settlement. It is realistic and perfectly achievable using our current technology.

With a daylight cycle similar to Earth's, reasonable gravity and sunlight, given the initial thermal impulse and seeded with life, the Red Planet could easily be turned into a second Earth, hosting billions of inhabitants and opening the way to exploiting its mineral resources. Along with humans, myriads of micro-organisms, plants, fungi, and animals will settle on Mars, too. A new biosphere will emerge in the Cosmos.

As always, the synergistic approach is optimal, with numerous methods available to improve living conditions on the planet. Done right, the whole process will take around a millennium. A prolonged but undoubtedly rewarding enterprise.

Terraforming and settling Mars would turn *Homo sapiens* into truly multiplanetary species, and it will pave the way to other terraformation projects, inside our Solar system and beyond. We will learn new ways, and we will improve ourselves. We will leave our mark on Mars and Mars will leave its mark on us.

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CHAPTER 5

New Stars are Born

A big enough hammer fixes anything.
Anonymous (Murphy's Laws)

Abstract:

Another valuable target is at our ease. The two gas giants of the Solar System, Jupiter and Saturn, host their mini-systems of various-sized moons. Among these, the four Galilean moons (Io, Europa, Ganymede and Callisto) and Titan are the largest.

While all these moons can be settled, they do not have enough light and heat to allow terraformation. The way to change this is by helioforming the two gas giants. Turning Jupiter and Saturn into mini-stars would efficiently thaw the major moons, creating atmospheres, hydrospheres and landmasses needed for life seeding.

Once triggered, the process might be even faster than on Mars. At the same time, some engineering effort is needed to correct the rotation rate of these tidally-locked worlds and ensure full human habitability.

Keywords: Galilean moons, Helioformation, Jupiter, Planetary spin, Saturn, Titan, Terraforming.

Considering the Martian example, let's go even farther from Earth!

At over 5 astronomical units (778,000,000 km) from the Sun, the realm of the giants starts. We are talking about the enormous gas planets: Jupiter, Saturn, Uranus and Neptune.

Jupiter has one-thousandth of the Sun's mass (and almost 318 times Earth's). Actually, it is 2.5 times heavier than all the other celestial bodies in the System (except for the Sun, obviously) together! Saturn (located at some 9.6 astronomical units from the Sun) has around a third of Jupiter's mass, while Uranus and Neptune are much smaller (we will put them aside for now).

So, huge and made of gas. Actually, each one has a core the size of Earth, made of rocks and ice. Yet, when the Solar System formed, these planets accumulated eno

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enormous amounts of gas, mostly hydrogen and helium, forming successive layers dominated by solid, "metallic", then liquid and gaseous hydrogen (Fig. **5.1**) [1, 2].

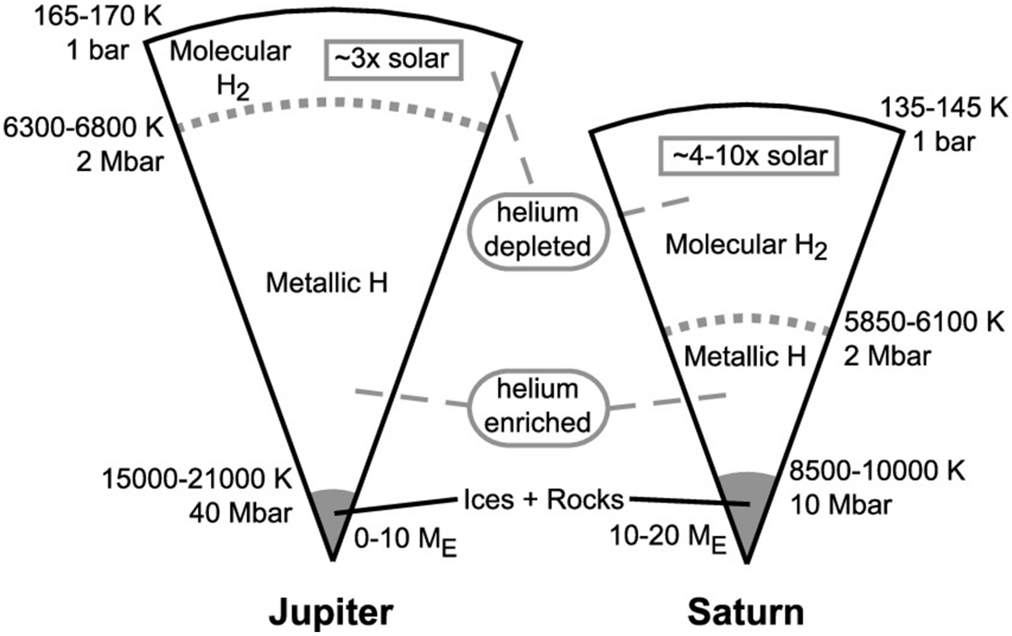

Fig. (5.1). The internal structure of Jupiter and Saturn [1].

These are surely not places where you would want to live! However, each gas giant has its system of satellites, some having impressive sizes. Practically, mini-systems within the Solar System (Figs. **5.2** and **5.3**).

79 natural satellites are orbiting Jupiter, most of them the size of usual asteroids. Four of them, on the other hand, have a remarkable potential for colonization. They are the moons called "Galilean" (named in honor of their discoverer, Galileo Galilei): Io, Europa, Ganymede and Callisto.

Saturn has 82 moons, of which only Titan has reasonable mass and gravity (Fig. **5.3**).

Yet, before initiating any terraforming process, there is a big issue: light. Jupiter and its moons receive flux of sunlight below 4% of the one reaching Earth, and there is not the slightest chance for photosynthesis to occur.

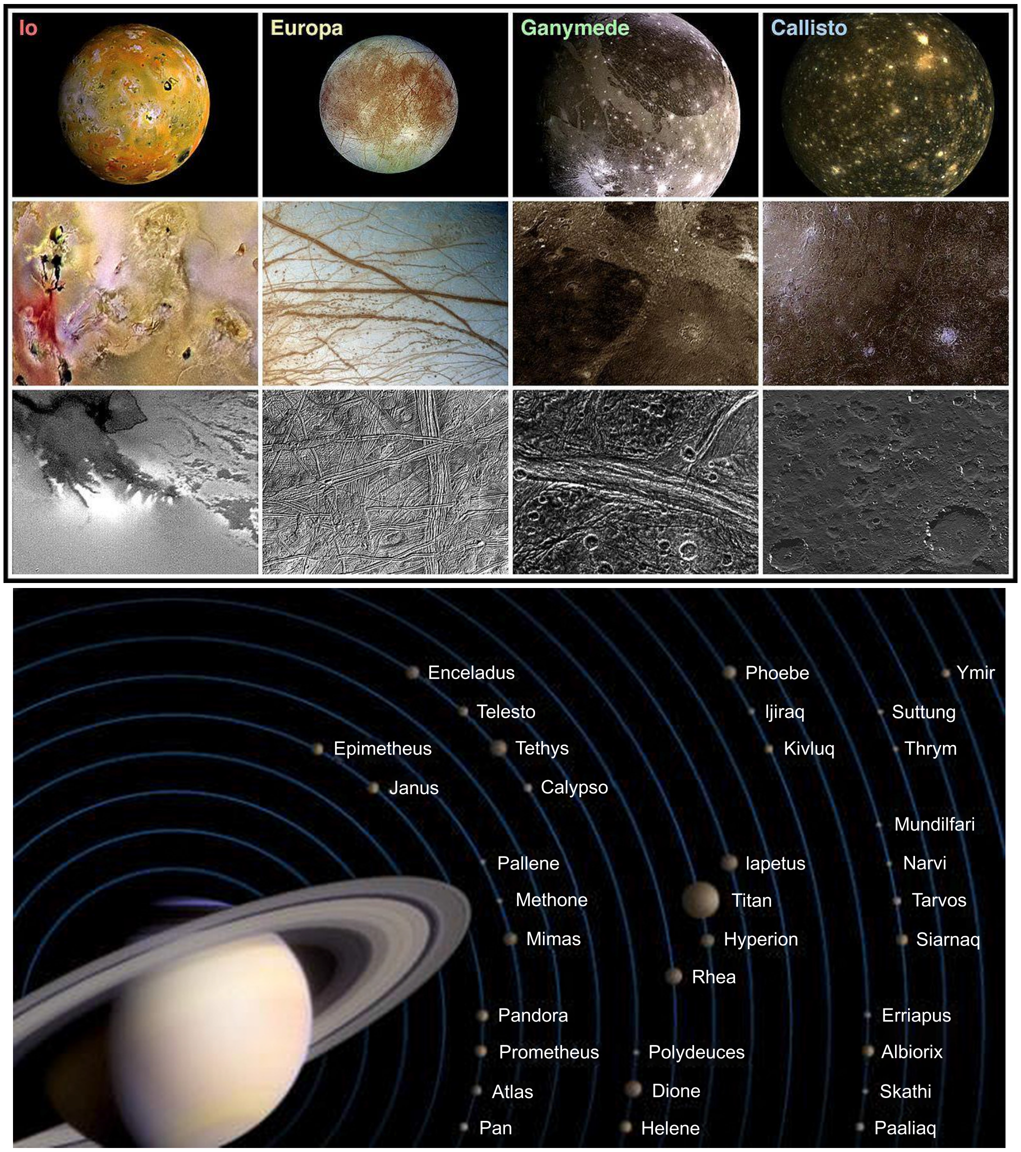

Fig. (5.2). Galilean Moons (the main satellites of Jupiter; with surface images) [3]; the moons of Saturn [4].

There are various proposed means to increase the amount of light, by using permanent orbital reflectors, similar to those used for terraforming Mars [3 - 5]. The problem, in this case, is that we would need some mirrors 12-15,000 km in diameter (wider than each moon itself). And this would be extremely difficult for obvious technical reasons [6].

So, it might seem that the Jovian and Saturnian systems are condemned to eternal darkness and freeze. But, maybe we have that big enough "hammer" needed to fix the problem. A nuclear one!

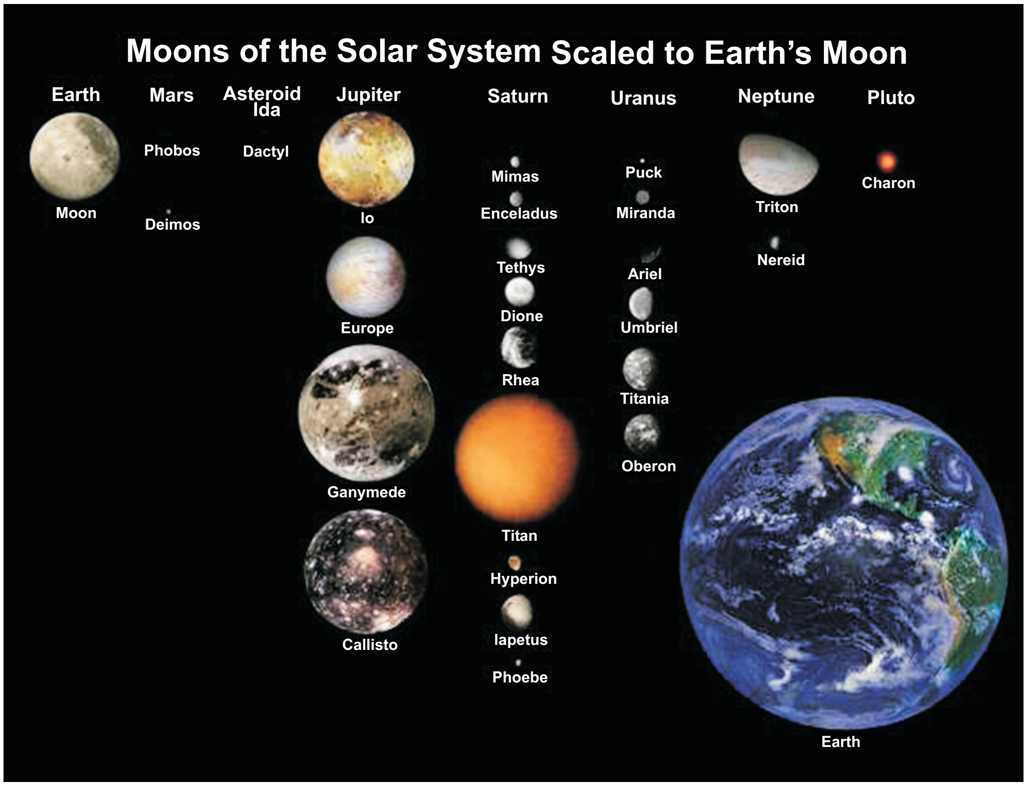

Fig. (5.3). Comparative sizes of some moons in our Solar System [5].

5.1. IGNITING THE GIANTS

You remember, of course, those giant planets are mostly made of hydrogen, helium, and other gases. It is a composition more similar to that of a star than that of the familiar telluric planets.

Surely, it is facile to call Jupiter a "failed sun". Considering the mass difference, it would be as logical as calling any larger asteroid a "failed Earth".

And still, what is the actual difference between Jovian planets and stars? At a mass 13 times greater than Jupiter's, the huge pressure exerted by gas layers leads to a spontaneous and self-sustained nuclear fusion reaction of deuterium (^{2}H, the heavier and rarer isotope of hydrogen), generating light and heat. Such a celestial body is called a *brown dwarf*, because the amount of light produced is not really impressive.

At the equivalent of 75 Jovian masses, pressure and temperature in the object's core become high enough to sustain the fusion chain reaction of protium (^{1}H, the common isotope of hydrogen). Such a body generates lots of light and heat, and it is considered a proper star [7].

Obviously, to supplement Jupiter's mass 75 times is a daunting task. But maybe we do not have to do it. The above-mentioned mass is that needed to "trigger" the thermonuclear reaction naturally, but we might have some alternatives. The process of transforming a gas planet (or a brown dwarf) into a star was called *stellification* or *helioformation* (meaning "the creation of a sun").

In 1982, Arthur C. Clarke imagined, in "*2010: Odyssey Two*", a way in which some mysterious, self-replicating, extraterrestrial entities turn Jupiter into a star, by means of an undetailed compression mechanism [8].

Seven years later, Martyn Fogg came up with a practical solution. More precisely, it involves capturing and manipulating a small black hole.

Black holes are bodies of enormous density, thus, a huge mass concentrated in a very small volume. They are usually formed following the implosion of large stars and have an extreme gravitational pull.

In this case, we are talking about an object weighing around 6×10^{20} kg (the mass of a big asteroid). The black hole would be directed (through gravitational means, similar to those proposed for moving asteroids) towards Jupiter's core, and the resulting pressure caused by its gravity would induce a fusion chain reaction inside the planet [9].

Surely, a black hole is not really something you may find at a supermarket. But it is not as rare as you may think, either. Besides stellar implosions, black holes can result from unclear events happening at the beginning of our Universe, or even high-energy subatomic collisions that occur regularly.

Thus, some scientific studies suggest that such objects, of subatomic sizes, pass through the Earth daily, without noteworthy effects [10]. Furthermore, due to cosmic ionizing radiation showers, others may be constantly produced in our planet's upper atmosphere [11].

This does not mean that, at this time, humankind has any idea on how to trap and aggregate such micro black holes, which also have extremely short lifespans. But, while black holes might not be available, we cannot say the same thing about nuclear warheads.

At the beginning of the ‘90s, there were some speculations concerning the existence, within the American military establishment, of some thermonuclear helioformation studies [12]. The idea also caused some concern during the controlled crash of the Galileo space probe into Jupiter’s atmosphere and the Cassini probe into Saturn’s. The rumors of an accidental helioformation (with unknown effects on our planet) were also fueled by a mysterious dark spot detected by some astronomers on Jupiter’s surface, following the former impact [13 - 15].

The main reason these concerns are unfounded is that radioisotope thermoelectric generators (RTGs) powering such probes are not bombs! They simply do not contain the right type of plutonium. Unlike the "explosive” ^{239}Pu, isotope ^{238}Pu decays relatively slowly, generating radiation and heat, but it is not fissile, even at high pressures.

However, this theme got out of conspiracy theories and opened the way to a truly serious question, that stimulated scientists to begin doing the maths: what happens when you detonate an atomic bomb inside a large mass of hydrogen?

The phenomenon is rather familiar since it is exactly the principle behind the thermonuclear weapons, the terrible hydrogen bombs, able to release megatons of energy and wipe out entire metropolitan areas from the face of the Earth. Briefly, a nuclear fission trigger explodes, causing temperatures to quickly surpass 35,000,000°C, the value at which compressed hydrogen within the bomb starts going through nuclear fusion reactions, generating much higher energy and temperatures up to 100,000,000°C.

Of course, what you see above is the ultra-simplified principle. H-bombs use heavy hydrogen isotopes (deuterium and tritium: ^{2}H, respectively ^{3}H), or, currently, deuterium-lithium nuclear fusion [16].

Are the giant planets ready to host thermonuclear reactions?

First of all, the two celestial bodies contain relatively high amounts of deuterium. Exactly how much? Estimates vary significantly, but there is a ratio of ^{2}H:^{1}H somewhere around 10^{-4}-10^{-5}. Values similar to those on Earth, just that here we are talking about huge planets mostly composed of hydrogen [17, 18]!

What is interesting is the distribution of this isotope. Calculations made by some specialists show a tendency towards its sedimentation. Thus, around 10% of the

Jovian deuterium could form a compact layer (with a ^2H:^1H ratio of around 10^{-3}), a few kilometers deep, somewhere at a depth of 60% of the planet's radius.

Furthermore, the such distribution would allow the existence of natural deuterium fusion reactions (forming tritium and, through its decomposition, ^3He). It is known that Jupiter releases more heat than it receives from the Sun. The exact mechanism is yet unknown and is usually attributed to atmospheric compression, but some researchers link it to internal fusion processes.

This model could be applied to all gas planets in the Solar System [19] and could better explain the cases of ultra-hot Jovian exoplanets (KELT-9b reaches the impressive temperature of 4,300°C in its upper atmosphere) [20].

The second factor is mass and, implicitly, pressure. There is an entire discussion on how a gas planet's mass could or could not sustain fusion. Simple logic tells us that the mass needed to "break" the Coulomb Barrier (the electrostatic repulsion between the protons of two nuclei), is greater than the one needed to mechanically hold hydrogen mass in one place.

The alternative would mean either to see stellar mass bodies that do not ignite, or stars that violently explode immediately after their ignition, which is not the case [7]!

Indeed, a key problem of nuclear fusion is that the rapid heating of the fuel leads to a dissipation tendency, thus ending the reaction. This is why compression is essential.

In the case of helioformation, fuel dissipation is unlikely due to the huge atmospheres of these planets. But, is it possible that Jupiter or Saturn will simply explode, ejecting most of the hydrogen to space (yes, there are even such concerns) [21]?

Well, no! The gravitational binding energies (a function of planetary mass and radius) of Jupiter and Saturn are over 2×10^{47}, respectively 2×10^{48}, which is more than 10^{10} times higher than any energy that could be released by an uncontrolled, explosive reaction of the entire internal deuterium masses!

Thus, giant planets are meant to remain in their current form, in case of a helioformation process. Is there any chance that such an action would fail? It certainly is, since nobody has ever tried such a thing before! Would it cost us a lot? No, since we have plenty of nuclear warheads, and the cost of a helioforming mission was evaluated at below $1.5 billion (less than half of the Cassini-Huygens mission, for example) [7].

However, calculations show there is a high possibility that the chain reaction will propagate throughout the Jovian/Saturnian atmosphere. How would it work?

First of all, materials used in modern aerospace structures can withstand pressures of tens of GPa (even 200 GPa, if we used carbon nanotubes) and temperatures up to 1,300°C. This means that the warhead-bearing probes would be able to descend down to depths equal to 2% of Jupiter's radius, respectively, 25% of Saturn's (the two planets have quite different densities). At that point, hydrogen density is high enough to reach a liquid or semiliquid state [7, 15].

The temperature released by a thermonuclear blast is around 100,000,000°C, inducing fusion reactions within the surrounding hydrogen mass. Density is high enough in the (semi)liquid layer where the detonation would occur, and the thermal and shock waves also propagate towards the planet's core, further compressing the hydrogen and preventing a fast dissipation. There is also the effect of collapsing edges of the cavity formed by the ascending hot gas bubble, that would also put pressure on subjacent layers.

Zones of high deuterium concentration would undergo fusion reactions. At 3×10^{-2} deuterium to protium ratio (even less, in case of compression), the nuclear reaction can propagate indefinitely within that atmospheric layer. The planet's hydrogen mass steadily enters a self-sustained chain reaction (Figs. **5.4** and **5.5**) [7, 22].

A small part (up to 10% of the total mass) of the outer atmosphere would be ejected in a wave of hot hydrogen, while the rest would turn into a mini-star. After a short time, the new sun would stabilize, hosting slow protium fusion reactions (once ignited, fusion reactions inside stars proceed very slowly; two protons need, on average, millions or billions of years to fuse; the enormous mass compensates this).

For safety reasons, the optimal period for helioforming is when the Sun and Jupiter/Saturn are in conjunction (meaning that the targeted planet and Earth are at their maximum distance, with the Sun between them). The amount of hydrogen our planet receives would be equivalent to less than 0.2% of our atmosphere's mass, while the Sun deflects most of it.

Instead, it is highly recommended to do it when Mars is as close as possible. The hydrogen ejecta would instantly heat the planetary surface and convert part of the local CO_2, through the Bosch reaction. The exothermic effect (up to 78°C, in the case of helioforming Jupiter and 16°C, for Saturn), plus a decrease in albedo (produced by graphite sedimentation) and the greenhouse effect of water vapor could be the trigger for terraforming Mars, as we saw in Chapter 4 [7].

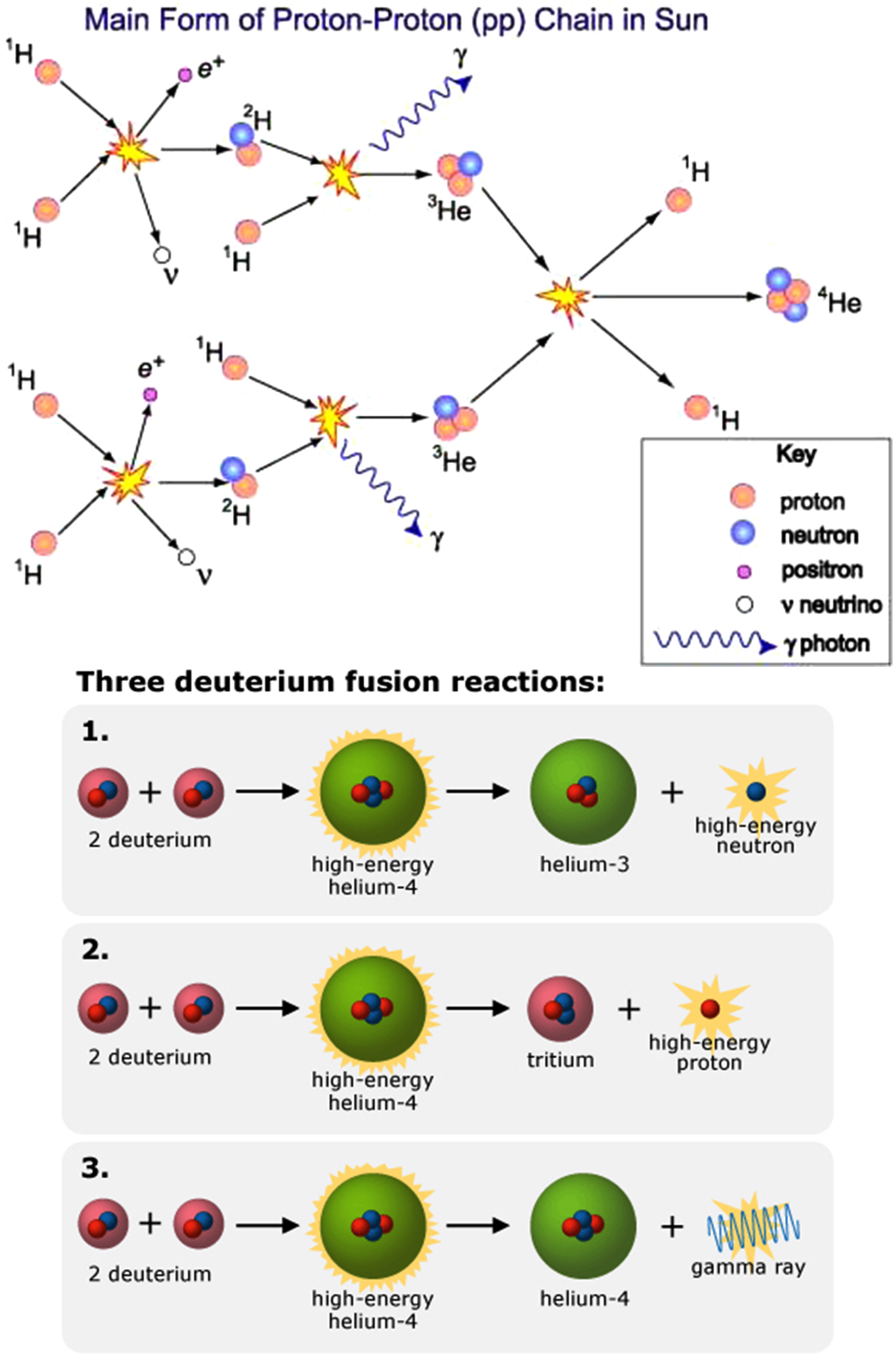

Fig. (5.4). Protium (^{1}H) fusion reaction inside stellar cores [23] and possible deuterium (^{2}H) fusion reactions [24].

In order to calm down any concerns, calculations clearly show that the gravitational and lighting effect on Earth would be negligible. If Jupiter disappeared for good, the only consequence would be making our orbit less elliptic, with lower differences between seasons. And, due to the distance, the amount of incoming light from the new star would be insignificant – we would just see a somewhat brighter spot in the night sky [7].

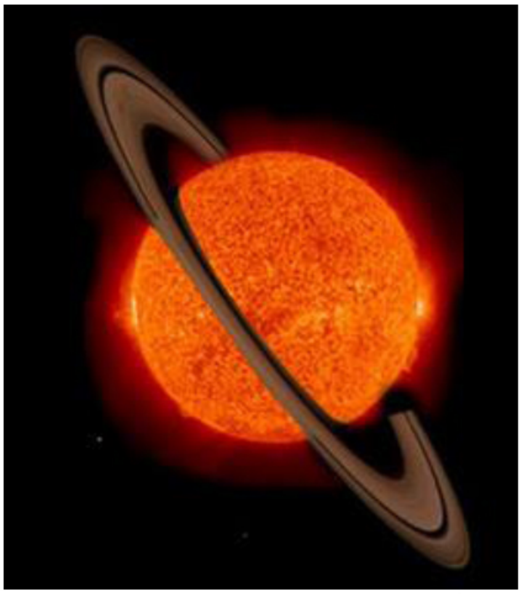

Fig. (5.5). Artistic image of a helioformed Saturn (although the process could perturb the ring system) [27].

Some scientists even consider helioforming a prophylactic measure [23, 24]. You are probably familiar with the theory of the metallic, dominantly ferrous core of most planets. Well, there is also an alternative theory, stating that the cores of most planets (including gas giants) have a high uranium content, somehow functioning as natural nuclear reactors [25]. In this case, helioforming could be triggered spontaneously. So, it would be a good idea to do it in a controlled manner, with minimal effects on Earth [26]!

How would the newly transformed celestial bodies look like?

It is difficult to imagine, since no such naturally or artificially helioformed planet was ever observed in any known planetary system. If we extrapolate the relation between main sequence stars, according to which a star 10 times lighter than the Sun would have a luminosity 300-1,000 times lower, a helioformed Jupiter would be 10^{-10} times dimmer [23, 27, 28]!

However, we are definitely not in the main stellar sequence. According to T. Angelov, the luminosity of a star is proportional to its mass, raised to the power of *q*. Jovian mass is one-thousandth of the solar one. The *q* factor varies somewhere between 2.7 and 4, with a "flattening” tendency for small masses. Thus, we are talking of a luminosity equal to 10^{-6}-10^{-9} of the solar one [29].

And yet, it seems that this flattening is even more pronounced. A study conducted on various classes of dwarf stars found luminosity ratios of 10^{-5}-10^{-6} in objects having 5% of the Sun’s mass. And these are brown dwarves, not subject to helioformation and, thus, lacking protium fusion reactions. In objects just above this limit, the ratio increases to around 10^{-3}-10^{-4} of the solar luminosity. Even more, some young brown dwarves have a ratio above 10^{-3}, at a mass close to the upper limit of this class [30].

For a helioformed Jupiter/Saturn, it is reasonable to assume an absolute luminosity of at least 10^{-4}-10^{-5} of the solar one.

Fogg estimates a similar value, for the first few tens of millions of years of the new star’s evolution. A luminosity around 10^{-4} and a surface temperature of 1,000°C [9].

And 10^{-4} is just perfect! Why? Radiance (the light flux received by a planet or any other body, from a specific light source) is directly proportional to luminosity and inversely proportional to the square of the distance:

$$I = L/(4\pi\ D^2)$$

And the distances between Jupiter/Saturn and their main moons are about a hundredth of the Sun-Earth distance. Thus, the differences in luminosity and distance would perfectly compensate for each other. The above-mentioned bodies would receive enough light and heat to help them reach temperatures similar to those on Earth or, at least, Mars [7, 9].

5.2. FIVE SISTERS

Jupiter and Saturn have lots of satellites. Yet, just some of them are of interest for now (see Table **5.1**).

As you can see, some of these celestial bodies are either too close or too far and, most of all, some are too small, so their gravitational pull is very weak (satellites not mentioned in the table are even smaller). For the moment, let’s focus on those having a gravitational acceleration higher than 0.1 g (for comparison, the Moon has 0.165 g). We saw above that low gravity means difficulties in holding an atmosphere in the long term.

So, we are only left with the five largest moons, written in bold letters: Io, Europa, Ganymede, Callisto and Titan.

Another important aspect is the distance to the helioformed planet. As shown above, the recommended values are those around 1% of the distance from Earth to the Sun (meaning an astronomical unit: 149.6 million kilometers), respectively, from the other telluric planets to the Sun (0.387 AU for Mercury, 0.723 AU for Venus, 1.523 AU for Mars) [2].

So, all the five bodies mentioned would fit. At this point, it is difficult to evaluate the effects of helioformation, but, as we saw, Fogg estimated initial temperatures close to 0°C for Europa (and also for Io), respectively, "Martian" temperatures (between -80 and -60°C) for Ganymede and Callisto [9].

Table 5.1. Some of the largest moons of Jupiter and Saturn [31].

Planet	Moon	Radius (×Earth Radii)	Distance from Planet (×Millions km)	Gravitational Acceleration (g)
Jupiter	**Io**	**0.286**	**0.421**	**0.183**
	Europa	**0.245**	**0.670**	**0.134**
	Ganymede	**0.413**	**1.070**	**0.146**
	Callisto	**0.378**	**1.882**	**0.126**
	Himalia	0.013	11.388	0.006
	Amalthea	0.013	0.181	0.002
Saturn	**Titan**	**0.404**	**1.221**	**0.138**
	Rhea	0.119	0.527	0.026
	Iapetus	0.115	3.560	0.023
	Dione	0.088	0.377	0.023
	Tethys	0.083	0.294	0.014
	Enceladus	0.039	0.238	0.011
	Mimas	0.031	0.185	0.006

Of course, another problem is the evolution of these objects' orbits, once Jupiter/Saturn eject one-tenth of their mass at ignition. Simulations show that the orbits should maintain their current shapes, although, in the long term, a slightly increased distance from the giant planets is possible [31].

The habitablity period of these worlds is another disputable question, since no helioformed gas giant was ever studied. The amount of nuclear fuel inside Jupiter and Saturn is, obviously, 1,000 and 3,000 times smaller than inside the Sun. The Sun has an estimated total lifespan of 10 billion years. Still, the mass-lifespan relation is not a proportional one! On the contrary, smaller stars live longer! A star having half the Sun's mass can "function", on average, for about 200 billion years, while one has one-tenth of the solar mass, 2 trillion years [23]!

This does not mean that such stars do not undergo expansion/contraction cycles in the long term. Fogg estimated the habitability period of Europa to 10 million years, that of Ganymede to 60 million years, and that of Callisto to 110 million years [9]. Anyway, these are significant periods seen from a human historical time scale.

Coming back to the five moons, how can we transform them into new homes for humankind? Well, now we might be on shaky ground.

You have certainly heard in the news that one of these moons (usually Europa) has an ice crust over a salty "ocean" that could even host life. And you probably imagined something like a polar landscape here on Earth.

Well, that is not an ice shelf, but a layer tens or hundreds of kilometers thick, equivalent to the terrestrial lithosphere. And the "ocean" is not really an ocean, but the moon's mantle, with an adequate thickness (Fig. **5.7**)!

Such structures mimic quite well what we find on Earth: plate tectonics, rifts, volcanic activity *etc.* Just that the composition of these bodies is dominated by lighter elements, (which is also obvious when considering their low densities). They are worlds of ice and water masses. Some potential "blue planets", even more than Earth.

Of the five great moons in question, three (Europa, Ganymede, Callisto) have this structure Fig. (**5.6**). Titan is identical, but it also features a thick atmosphere, while Io is rocky, so we will put it aside for now.

Let's take Ganymede as an example, being the largest of these worlds! In this standard structure, we obviously find a surficial ice crust, of variable thickness. When we talk about ice, we do not only mean frozen water. The crust's reflectance would imply a 10-50% percentage of other chemical compounds: carbon dioxide, maybe some hydrogen cyanide, and hydrogen sulfide. Add some clay materials and various organic compounds released by the local volcanism (water eruptions).

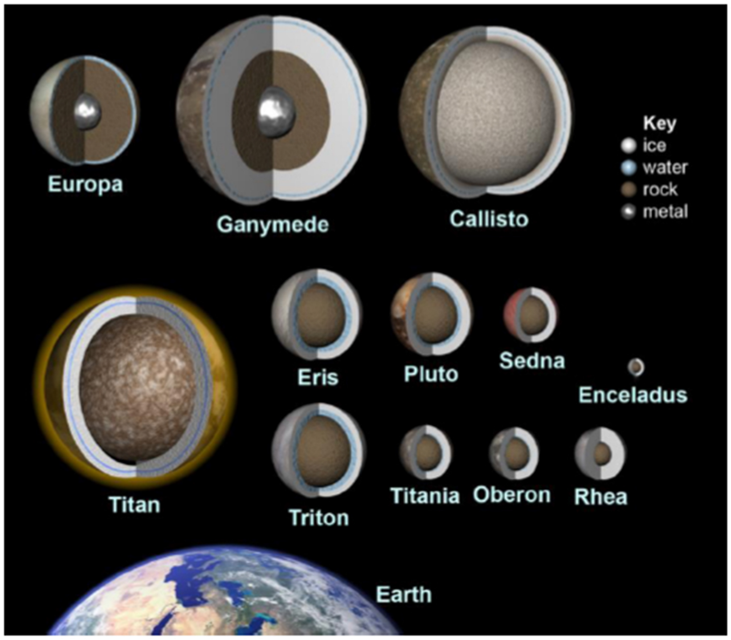

Fig. (5.6). Internal structural models of the "ice worlds" in our Solar System, with the proportional distribution of metallic and rocky cores of solid and liquid water, respectively [32].

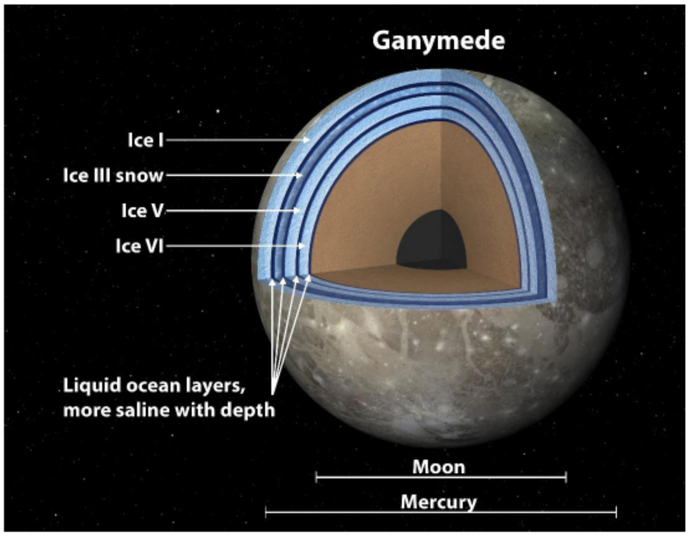

Fig. (5.7). Ganymede as a model Jovian world: internal structure and comparative size [33].

Part of this crust sublimates, forming water vapor and, through photochemical dissociation, molecular oxygen (0.2-1.2×10^{-6} Pa). The tiny atmosphere also contains some ozone and hydrogen. Unlike other similar bodies, Ganymede is enclosed in its own magnetosphere, which still does not prevent radiation coming from Jupiter's magnetic field to shower the satellite in daily doses over 100,000 times higher than the terrestrial ones [32 - 34].

While researchers usually agree on the core as being composed of metal and silicate rocks, more problematic is what lies between the crust and core. There are various models, including compact layers of saltwater, "exotic" forms of ice or mixed structures (some sort of a slush, extending kilometers deep), but the most recent studies indicate, for Ganymede, the structure shown in Fig. (**5.7**).

Thus, there are layers formed of different types of ice and, between them, liquid "oceans" of different salinities. This can happen because, apart from the hexagonal crystalline ice we are so familiar with, the Universe hosts at least 17 other types of ice, including amorphous ice or monoclinic, tetrahedral, rhomboidal crystalline ice *etc.* Many of these ice types are heavier than liquid water!

According to this model, the first layer of ice, thus, the moon's crust, would have no less than 150 km of thickness [32]! An extremely important aspect to consider because in the future terraformation of such types of celestial bodies, there is a big "NO" our descendants need to keep in mind: do NOT break the ice crust! Dismantling this lithosphere would result in some integrally aquatic worlds, having oceans tens/hundreds of kilometers deep (the first liquid layer of Ganymede is 100 km thick), eventually keeping some areas of the polar shelf. Unless we grow gills in the future, such a place would not be really suitable for mass settlement!

Otherwise, surficial ice seems to provide the materials needed for atmosphere building. For instance, carbon dioxide seems to be quite abundant. Spectroscopic analyses performed in various regions of Ganymede's crust found 2.4-21.3% percentages of carbonic ice, depending on latitude and general granulation of the crust [35].

Let's imagine this moon after helioformation occurs (actually, this planet, since now it would orbit a proper star). If temperatures reach values similar to terrestrial (or, at least, Martian ones), as we estimated above, larger and larger amounts of CO_2 and water vapor (plus methane, ammonia and other gases trapped there) would sublimate, creating a thicker and thicker atmosphere. All these are greenhouse gases, so releasing them would lead to a temperature increase and to new amounts of gases evaporating.

This is exactly the Martian scenario, that of a chain reaction, described in detail in (Subchapter **4.1**). In time, we would have a new world, with its own atmosphere, temperatures suitable to life and a complete hydrological cycle.

Just as in the case of Mars, there are some uncertainties regarding the exact amount of nitrogen available. It is assumed that part of the crustal ice is, actually, frozen ammonia. We do not know the exact percentage, but by extrapolating data from Titan, we can assume that the amount is relatively large on all these icy worlds. Its evaporation would produce gaseous ammonia, with a greenhouse effect, but unstable in the long term, decomposing to molecular nitrogen and hydrogen. This way, the icy moons could harbor larger nitrogen reserves than Mars.

However, if this prediction proves to be partially wrong, nitrogen can be imported from the Outer Solar System or, especially, from Titan, where it seems to be present in excess, in the atmosphere, the crust and the layers below the crust [36].

And, as well as in the Martian case, building up biospheres on Europa, Ganymede and Callisto should also start with *Chroococcidiopsis*, *Anabaena* and the plethora of psychrophilic, hypoxia and radiation-tolerant cyanobacteria and microalgae. Followed by lichens, peat mosses, flowering plants *etc.,*

There is only one major difference. A substantial part of the new atmosphere would be formed of water vapor, which, in the long term, decomposes into oxygen and hydrogen. Thus, the sister-planets would have a partially oxygenic atmosphere from the very beginning.

If you look again at Table **4.3**, you will find out that the longest stages of terraforming are the ones needed to convert the atmospheric CO_2 to O_2, through photosynthesis. In the case of Jovian and Saturnian moons, the entire process could be shorter by over half a millennium! We would get a breathable and habitable environment much earlier than on Mars. Including a protective ozone layer.

There is still, however, the problem of the planetary crust, which would become progressively thinner, as the atmospheric pressure increases. Is there a risk of creating waterworlds?

Europa is the most prone to such an ending of all the icy worlds. Estimates vary, but it seems the crust of this moon has a thickness of just 20-30 km [37].

On average, a compact ice layer melts at a rate of around 3.7 mm a day, per Celsius degree. At an average temperature of 15°C (like that on Earth), a 20 km ice crust would melt in about one millennium.

And yet, such a scenario involves all three mechanisms causing ice melting: conduction, radiation and, the most effective, convection. But convection is mainly due to a continuous water flux forming beneath the ice layer, a mechanism that could not work on these moons, where the base of the crust is located tens of kilometers below [38].

More likely, the process would be similar to permafrost melting, in the cold regions of Earth. Soil topography and structure and also vegetation strongly influence the melting rate. A vegetation cover (lichens and mosses), for instance, maintains a low temperature at the permafrost layer's surface. 10 cm of vegetation decreases soil temperature by 3°C during summer (due to a lower thermal conductivity). Forestation reduces the thickness of snow layers, also decreasing temperatures at the permafrost-air interface [39].

There are several possible solutions. For example, we can strengthen ice surfaces with plant fibers (I do not think that any future society will run short of sawdust or paper residues), producing a layer of pykolite (see Subchapter **2.3**), which is much harder.

Or, we can set the climate of the respective planets in a way that protects the ice crusts. Surely, the average temperature here on Earth is around 15°C, but there is no need for all terraformed planets to be absolutely identical. Romania has an average temperature of 10°C, while in other countries, it is even lower, without preventing human settlement. We would probably all want to live in the Bahamas, but Alaska is habitable, too!

A planet's climate is influenced by many factors, including atmospheric composition (and the presence/absence of a greenhouse effect) or albedo. The future society will somehow need to master certain geoengineering techniques (practically climate control), not just for terraforming, but also to stabilize Earth's climate. This is because there might be no other possibility to fix the decades of irresponsible pollution. Or because our planet's climate could also deteriorate from natural causes: we may need to start thinking about how to avoid the next ice age!

Among the methods that can be used to cool a planet, there is spraying reflective aerosols into the atmosphere (especially sulfur compounds; the process is somewhat similar to the effects of volcanic eruptions and, luckily, the "neighboring" Io is volcanic enough to constantly produce such chemicals) [40] or, even better, stimulating the activity of marine plankton. After all, microalgae are the ones responsible for most of the CO_2 consumption on Earth, while they can also influence the planetary albedo [41].

There are, however, some good news that might spare us from such problems. Gravitational field analyses have shown the existence of some irregular masses buried inside Ganymede's ice crust. It seems that they are compact areas of rocks or rock-ice mixtures. It is still unclear whether they are of internal or asteroidal origin, whether they are supported by ice layers or protuberances of moon's rocky core. We know, however, that they reach close to the outer surface [42].

Thus, Ganymede has continents! Melting the crust would leave, in this case, some land areas on which plant, animal and human colonists could settle.

There are even brighter prospects for Callisto. Once, during the first stages of the existence of the Jovian satellites, while they were still hot and fluid, heavier minerals gradually sedimented towards their center while water and other lighter compounds raised towards the surface, causing the current stratification.

Only in the case of Callisto, farther from Jupiter, the cooling went fast enough to prevent this stratification from being complete. Thus, a large part of the water remained chemically-bound to mineral layers or, as ice, mixed with them. The structure of this moon is more homogenous than that of other similar satellites and, if Ganymede has continents, the same will certainly be true for Callisto [43].

Furthermore, there is a thick lithosphere, comparable to that on Ganymede and the moon is located outside Jupiter's radiation belts (the current incident radiation dose, of 0.1 mSv/day, is easily tolerable by the human organism), features that make Callisto one of the easiest to colonize worlds of the Solar System [3, 44].

Titan, Saturn's main moon is, in regard to its internal stratification, somewhere between Ganymede and Callisto. Thus, as a terraformed planet, it will also have continental masses [43].

Titan's uniqueness resides in its atmosphere. The atmospheric pressure is over 146 kPa, meaning 145% of the terrestrial one, and it is mostly made of molecular nitrogen (more than 94%). Current surface temperatures are extremely low (somewhere around -180°C), but things will change, once Saturn is helioformed. New amounts of gases will be released from the crust: water vapor (which will generate oxygen), ammonia (a nitrogen source) and methane.

Titan is also the "gas station" of our Solar System, harboring impressive amounts of hydrocarbons (methane, ethane, propane), found in both the atmosphere and on the surface, in liquid form and probably also trapped inside the ice [45].

To many readers' disappointment, a large part of these reserves will need to be sacrificed on the altar of habitability. Let's hope our future economy will be less dependent on such chemicals.

Light hydrocarbons will evaporate, thickening the atmosphere (for the moment, there is 5.65% methane) and, by reacting with oxygen, will generate carbon dioxide.

As we saw in the previous chapter (see also Table **4.1**), the upper tolerable limit of atmospheric pressure, to humans is around 500 kPa. Above this value, gas embolism and nitrogen narcosis occur.

It is unlikely that Titan's atmosphere will ever reach this value, but lowering the pressure is always a good idea, in order to ensure a pleasant living environment.

To consume excess CO_2, photosynthesis is necessary, while for excess nitrogen, the main solution is nitrogen fixation. You guessed it: *Anabaena*, *Chroococcidiopsis* and all the other wonderful psychrophilic cyanobacteria! And, to continue the process, microbial nitrification provides a convenient nitrogen sink mechanism.

Bacteria such as those belonging to the genera *Nitrosomonas*, *Nitrosococcus*, *Nitrospira*, respectively *Nitrobacter*, *Nitrospina*, *Nitrococcus*, *Nitrospira* oxidize, in two stages, nitrogen to nitrites and, then, to nitrates. The process takes place in upper soil layers and also in aquatic environments. Nitrates are soluble and readily mobilised, but can also accumulate, forming compact deposits [46].

And, just like on Mars, vegetation, swamps and peat bogs can function as concentration and storage systems for carbon and nitrogen.

Anyway, there are many worlds in the Solar System that will be willing to get some of Titan's excess nitrogen. We discussed this in the previous chapters: a combination of orbital rings, liquefying stations and ballistic devices can provide nitrogen to Mars, Io, the Moon or Mercury (though, this "*Chroococcidiopsis* export" will probably require long periods of time).

Surprising enough, one of the main problems of a newly-terraformed Titan would be pollution. The planet hosts huge amounts of hydrocarbons, many located on the surface [47]. Heavier, non-volatile fractions, could persist for a long time in water bodies and soils. Fortunately, there are numerous bacteria (species and strains of *Pseudomonas*, *Achromobacter*, *Arthrobacter*, *Micrococcus*, *Nocardia*) and fungi (*Penicillium* sp., *Verticillium* sp. *etc.*) that see petroleum as delicious food. Consider that, no matter how long they are, hydrocarbon chains are not so chemically different from fatty acids, familiar to all organisms, and the aforementioned species use the same enzymatic pathways to oxidize them to CO_2 and water [48].

The situation in Europa is slightly more difficult. With a relatively thin ice crust and located right in the middle of Jupiter's radiation belt (an effect of the magnetosphere, similar to Earth's Van Allen Belts, but at a much larger scale; the daily radiation dose at the moon's surface is 5.4 Sv, enough to kill any human being quickly) [3].

We already saw that climate control prevents an excessive increase in average temperature and good soil and vegetation cover can "save" the planet's icy lithosphere. If necessary, we can import asteroidal rock. And, if things go unexpectedly wrong, even water worlds can host human settlements, using the techniques mentioned in (Subchapter **2.3**). There are also some ways to build an artificial magnetosphere and shield the planet from radiation, as we saw in (Subchapter **4.3**).

Finally, among the five sister-worlds, Io is the strangest. Small, volcanic, lacking any atmosphere and strongly irradiated (36 Sv/day), it is also different from a structural point of view. It is a solid, rocky, dense object, with no water or ice layers.

Io is somewhat more similar to telluric planets, with a metallic core, surrounded by silicate rocks. Just like in other Jovian moons, the diverging gravitational forces of Jupiter and neighboring satellites cause its core to heat. Due to its proximity to Jupiter, this process is much stronger on Io, creating a molten core and mantle, whose magma frequently erupts, through a multitude of volcanoes.

The surface is solid, with lava fields, volcanic mountains and other landforms [3]. So, there is no problem with continental masses in this case, but quite the opposite!

The main problem is the lack of water. Although some potential ice deposits were identified, Io is probably the driest object in the Solar System. So, we will not have enough water nor volatiles for building an atmosphere, hydrosphere and biosphere.

Still, that does not mean terraforming is impossible. Once Jupiter is helioformed and the artificial magnetosphere created, it is possible that the very volcanism will lead to gas accumulation in the atmosphere. And, concerning water, ammonia or methane, Io is luckily located in the Jovian System, an area that does not lack such things.

The rest of the smaller and bigger moons, contain major amounts of ice, of all types [3, 49, 50].

Thus, the necessary chemicals can be brought by diverting and controlled crashing small-sized satellites or by ballistic means, even if the duration of the whole process would prove longer than for other Jovian moons.

So, within a few centuries, five new habitable planets would appear in the sky (Fig. **5.8**). While for Io there are some difficulties, the other sister-worlds (Europa, Ganymede, Callisto, Titan) seem to have all that is needed to initiate terraformation. And, up to this point, all this is possible by using our current technico-scientific knowledge. Basically, it involves the same strategies used for Mars.

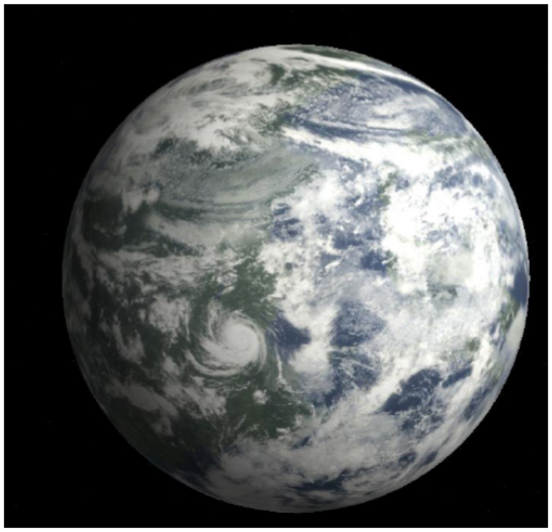

Fig. (5.8). Terraformed Ganymede; a model to Jovian and Saturnian moons [49].

We saw, in the chapter dedicated to Mars (Subchapter **4.3**), that there are also solutions to long-term problems, like low gravity or the continuous loss of hydrogen and other light elements.

Although it all seems perfect, there is another problem that is extremely difficult to solve. However, it is one that humankind needs to find an adequate answer to in order to pursue space colonization, in general. One that significantly affects terraforming Jovian and Saturnian moons.

5.3. HOW TO SPIN A PLANET?

The main moons of gas planets, our Moon and Venus and Mercury, have something in common. They rotate extremely slowly. The aforementioned satellites are tidally-locked, meaning they always show the same face towards the planet they orbit. Mercury has an extremely slow rotation (58 days), while on Venus, a day is literally longer than a year!

In such cases, terraforming becomes almost impossible: how to make a world habitable when one hemisphere is warm and lightened, while the other is cold, dark and hostile to life? Well, we could try, since recent data show that atmospheric circulation might somehow compensate for the lack of light on the dark side (in other words, not all the atmosphere would freeze and accumulate on this side), which would solve part of the problem for the Jovian and Saturnian moons (actually, only for their near sides) [51].

The situation becomes much more dramatic on the Moon and inner planets. Here all regions pass through day-night cycles, but these are much too long to allow vegetation to thrive.

Of course, there is always the option of installing reflective systems, to completely illuminate those planets: orbital mirrors of planetary size (a difficult solution, from a technical point of view) or swarms of smaller mirrors (feasible, but less efficient) [52].

So, it would be a good idea to see how to accelerate the rotation of a planet. Either way, such an innovation could be applied to many celestial bodies in our Solar system and beyond.

Maybe the most thoroughly studied case is that of Venus, a planet having a rotation period of 243 terrestrial days (the revolution period, thus the Venusian year, is only 224 days long, and the difference makes a Venusian "day", understood as a light-dark cycle, 117 Earth days long).

We know that one factor that slowly but steadily accelerates the planet's rotation is wind. High-altitude winds can reach speeds of 360 km/h, and, when hitting mountain slopes, create a pushing effect. Thus, each Venusian day gets shorter by up to 7 terrestrial minutes. This does not necessarly mean that in 24,000 years, a day on Venus will last as much as one on Earth. Titan features the same atmospheric super-rotation effect, without losing its synchronous spin [53].

So, we might try, on planets and moons having an atmosphere dense enough, to manipulate air fluxes, by geoengineering methods, in a way that creates constant winds blowing in the desired direction. To accomplish this, swarms of orbital mirrors could prove extremely useful.

Melting ice masses and rising ocean levels also accelerate planetary rotation (this can be applied to the icy Jovian and Saturnian moons). The same goes for changes in atmospheric composition. Or, the presence of life through oxygenating the atmosphere. However, all these only work over very long periods of time [54].

Among the factors that can slow down a planet's rotation are tides, through friction between water masses and continental shelves. There is a theory stating that this was the reason Venus reached the current rotation rate, starting from below 16 terrestrial days, in just 10-50 million years. Note that tides involve other planetary components, too, such as the mantle [55]!

A more "brutal", but effective way of altering a planet's rotation speed is by using controlled asteroid impacts. It was calculated that four metallic asteroids over 350 km in diameter and tangentially aiming at the Venusian equatorial region would lower the local day to around 11 Earth days, which is much more acceptable. The problem here is that we only know four asteroids over 350 km (and about 20 over 200 km), but also that we would need some extra 46 to make a Venusian day similar to the terrestrial one [52].

The good news is that this method could prove much more efficient for our Moon (having a mass 68 times lower than that of Venus), Mercury (14 times lighter) or the Jovian and Saturnian moons (Ganymede is 33 times less massive), needing less impacts, with a lower total mass.

We might not even need a direct impact. We mentioned above the "gravity assist" concept, already used to accelerate space probes: a close encounter with an object having significant gravity will alter the probe's trajectory and speed, as well as those of the celestial object involved. Of course, the change a spacecraft induces to a planet's trajectory is insignificant.

However, things change if, instead of the probe, we use a massive object, such as an asteroid. There are some researchers, like D. Korycansky, that consider using this method, in order to change planetary orbits. Flybys by an asteroid having 100 km in diameter, at distances around 16,000 km, repeated a million times, could save Earth from the swelling Sun, some billion years from now.

But, at a smaller time scale, such flybys can gradually accelerate a planet's rotation. Although maneuvering such objects is no easy thing, it is still a noteworthy option [56, 57].

We already mentioned mass drivers, as a way to transport nitrogen or carbon dioxide from the atmosphere of Titan, respectively Venus, towards other terraformable bodies. Systems of orbital rings, with space elevators, coupled with electromagnetic ballistic devices.

A properly directed mass ejection can alter the rotation rate of planets and large moons. This is accomplished through both the reactive effect and changing the mass of the atmosphere.

There are, however, some doubts regarding this method's efficiency: thousands of mass drivers would be necessary, working for centuries and ejecting atmospheric gas pellets, preferably, at near-relativistic speeds [57].

But, what would you say about using a transmission belt instead? Obviously, not the real object, but this is the principle behind a method put forward by P. Birch.

Briefly, an orbital ring would be built around the Sun, respectively, around Jupiter/Saturn. As we saw in Chapter 3, orbital rings are not necessarily extremely costly constructions. This one could be supported by a sort of a "solar sail" structure and would host a circular mass driver. It would propel pellets of matter (any kind of matter) to near-relativistic speeds.

The pellets would target an electromagnetic "rail", built around the planet's equator, where they would be launched back through semicircular sections and a parallel rail (Fig. **5.9**).

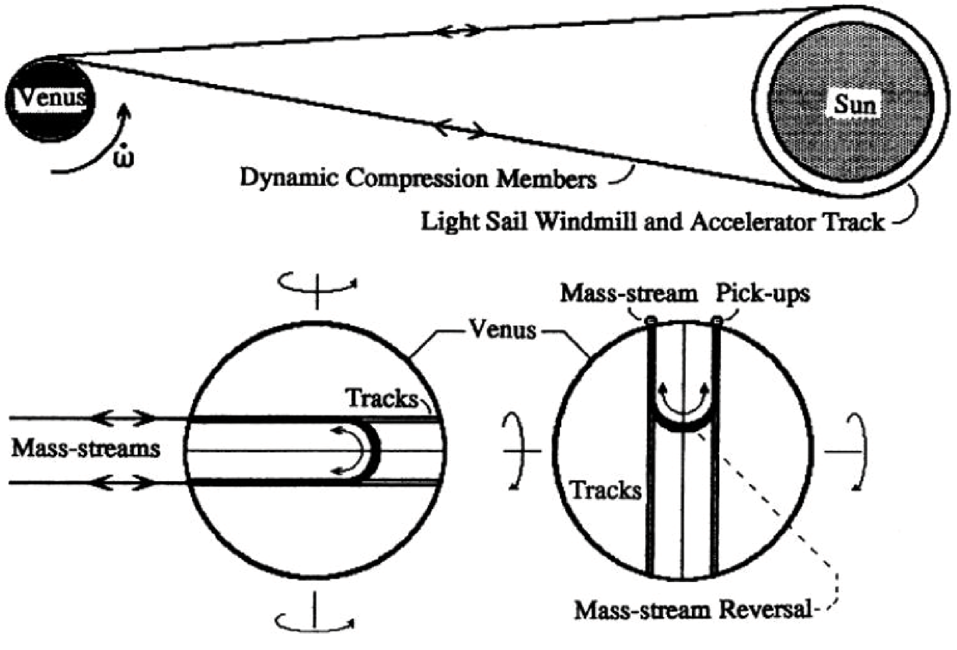

Fig. (5.9). Accelerating a planet's (Venus) rotation by using circular mass drivers [58].

The continuous pressure exerted by the pellet flux on the perpendicular components of this system, as well as the fast ejection, would accelerate the rotation of Venus to a 24 hours/day one in a relatively short time, maybe even as short as 30 years [58].

We can imagine other similar solutions, combining toroidal solar wind concentrators, like those proposed by M. Culaj for terraforming Mars (see Subchapter **4.3**), with mass drivers, hydrogen being the ballistic material used in this case [59].

Finally, maybe the most elegant solution is the one put forward by Freeman Dyson. More than half a century ago, the physicist imagined an electromagnetic "planetary spin motor”, that could alter a planet’s rotation. The purpose was to accelerate the spin of any celestial body up to speeds that would cause the self-disassembling, thus providing materials to build an eventual "Dyson sphere”.

If you really wish to turn any planet into such a self-destructive spinning top, I leave you the pleasure of finding a suitable energy source. For now and for our purposes, this principle is easily applicable to much lower energies.

Building such a planetary motor (Fig. **5.10**) should start by surrounding the respective planet/moon with massive, latitudinal electrical conductors. It is the same structure as that proposed for creating an artificial magnetosphere (Subchapter **4.3**) and Fig. (**4.13**), thus would serve a double purpose [60].

These installations would create a toroidal magnetic field, similar to a normal magnetosphere. Now, we just need some external magnetic fields for the motor to work. We are talking about a "cloud” of electromagnetic generators (at a distance up to around 100 planetary radii).

Those generators could be built on small-sized asteroids (or fragments of a larger one) and would emit magnetic fields perpendicular to the planetary one. These would induce periodic oscillation movements of the elements forming the "cloud”, towards and away from the planetary surface (for these reasons, these generators should be provided with solar sails or other compensation mechanisms, to avoid being ejected from orbit).

It was calculated that a flux of 0.01 tesla would be enough, and, as we saw, this is possible with our current technological means. The total energy consumption would be around 10^{17} W, reducing the Venusian rotation to 8 terrestrial days and 10^{18} W, for 24 hours. This means about one million times the current energy output of the USA, for instance, but we could use major energy sources, such as solar ones.

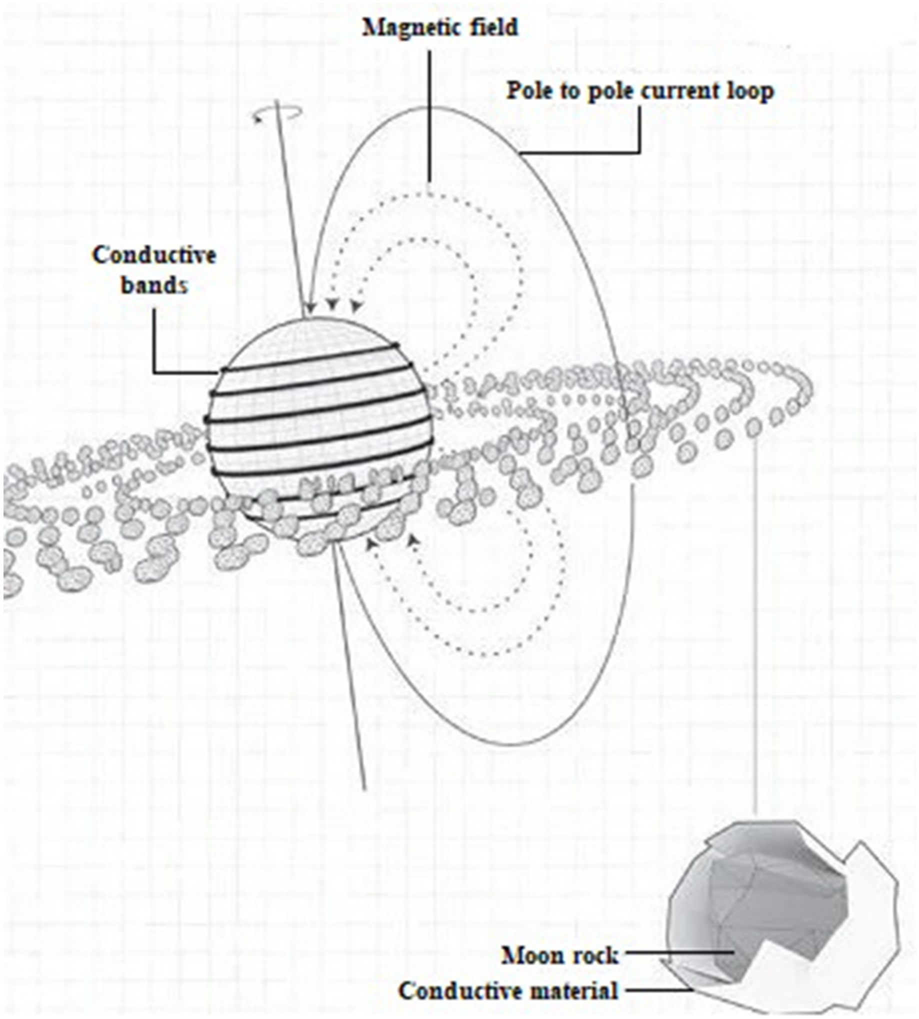

Fig. (5.10). The general design of a Dyson planetary spin motor [61].

More troublesome would be the total mass of the "generator cloud", of 5×10^{18} kg, one billion times the weight of the Palace of the Romanian Parliament, or the mass of a 100 km asteroid [61].

Anyway, the device could slow down the rotation of Venus to a much more reasonable 8 days in 280 years and to a terrestrial day in 2,220 years [62].

Note that the spin momentum applied to a planet is directly proportional to the cube of the radius and the square of the magnetic flux density. And Ganymede, for instance, at 2.297 times smaller radius, would require 12 times less energy. On the other hand, stronger magnetic fields would make the process more efficient, lowering the necessary time period.

Finally, since all the proposed solutions have their limits, maybe a combined approach would be better. For instance, a ring of asteroidal fragments (also useful for mining purposes, see Subchapter **3.2**), harboring electromagnetic generators, but also automated, mobile mirror complexes, that would selectively heat specific areas of the atmosphere, inducing the super-rotation effect.

All these, coupled with asteroidal impacts or flybys or bombing the surface with relativistic hydrogen pellets, would further reduce costs. And if we can do it on Venus, on other candidate planets, it would be a piece of cake.

CONCLUSION

Terraforming the planet-sized moons orbiting gas giants may be at the same time easier and more difficult than doing it on Mars.

If helioformation succeeds, and there are strong premises it can work, just by using some nuclear detonations, these bodies will quickly warm up, creating functional atmospheres and hydrospheres, while some percentage of oxygen will be present from the beginning. This way, the timescale of the whole process would decrease to somewhere around five centuries or less.

Ganymede, Europa, Callisto and Titan would become new abodes for life, including for billions of humans. Io is somewhat tougher, but can still be fixed through careful planetary engineering.

The major obstacle is the rotation rate of these moons. Since colonizing tidally-locked objects is not the best option possible, we need to change it. In this enterprise, we cannot avoid some very large-scale engineering and moving some asteroids around the System, but it can be done even at our scientific and technological levels.

The new Jovian and Saturnian star systems could stay habitable for millions of years and would dramatically increase the living space and array of resources available to humankind, allowing unprecedented development and opening new perspectives in our cosmic expansion.

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CHAPTER 6

Close Neighborhood

The face of the Mahdi shall shine upon the surface of the Moon.
Prophet Muhammad
(hadith narrated by M.I. at-Tirmidhi and J. as-Sadiq)

Abstract:

The Inner Solar System hosts several valuable planet-sized objects, that should be targeted by human colonization.

The Moon has the major advantage of being close to Earth, plus also having several useful features, such as low gravity (perfect for space launch) and useful mineral resources. It hosts vast areas suitable for enclosed settlements of limited terraformation. However, there are clues that, in time, it could be fully terraformed.

Mercury is a small, hot and dry planet, a tough target for future colonists. Planetary engineering could also work in these conditions, eventually allowing terraforming, or at least large-scale paraterraformation, under a planetary "shell".

Finally, in the Main Asteroid belt, Ceres could be the easiest terraformable object in the whole System. There are also technical solutions that could turn other planetoids and small moons into new homeworlds for humankind.

Keywords: Ceres, Moon, Mercury, Moons, O'Neill habitats, Parraterraformation, Planetoids, Terraformation.

Seven worlds are undoubtedly better than one. But it would be a pity if we settled for just that.

Towards the center of our Solar System, two telluric planets, similar to ours and well-lightened by the Sun, await us. Even closer, obviously, lays the Moon. An apparently deserted and unhospitable body, but having great economic value.

And it is so accessible to us that it would be really shameful if we did not take advantage and colonize it. The whole Universe would laugh at us!

Dan Răzvan Popoviciu
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So, three big worlds. And, let’s not ignore more problematic bodies: the large asteroids, like Ceres and Vesta, almost the size of small planets. Or small-sized Jovian and Saturnian moons: Rhea, Dione, Enceladus, *etc.,* There are obvious difficulties concerning their low gravity, but this does not mean that we cannot find suitable solutions.

Until now, Mars and the moons of Jupiter and Saturn taught us how to bring icy worlds to life, how to build up atmospheres, how to create a planetary magnetic field or to accelerate a planetary rotation to a day-night cycle similar to that on Earth.

These methods are partially applicable to the warmer region of the System, together with other specific techniques. For now, we will put aside the "jewel in the crown”, Venus, and we will focus on our little neighbors.

6.1. GREEN MOON

At "just” 384,000 km from us lays an orb that has lightened our nights and captivated our imagination since the dawn of time. It is our only natural satellite, the Moon (Fig. **6.1**).

Fig. (6.1). The Moon as seen from Earth [1].

Its diameter is a bit larger than a quarter of Earth’s, its mass is eight times lower, while the gravitational acceleration is one-sixth of the terrestrial one (and half of the Martian one). The atmosphere, mostly composed of noble gases, is negligible in terms of mass and pressure.

The average temperature is somewhere around -50°C, but don't be deceived! Extremes reach really unpleasant values: -170°C, respectively 120°C. The revolution period around Earth is 27 days and 7 hours, during which it shows us the same hemisphere. This also means that the daylight cycle of the Moon has the same duration.

Its structure and composition largely resemble that of Earth, out of which it was formed 4.6 billion years ago. The magnetosphere is extremely weak. The surface is arid, with small amounts of ice in the circumpolar regolith, some shaded craters (1.6 billion tons), and other amounts chemically bound to the regolith (up to 0.1% of the total mass). It will have quite an economic potential, in the future, due to ^{3}He reserves [1, 2].

As for the compounds necessary for life, it seems that Lunar regolith is not really rich in carbon (0.001-0.028%, generally as small calcium carbonate inclusions) and nitrogen (0.001-0.016%),[3] even if some findings suggest somewhat higher quantities, under the form of nitrates and ammonium salts. Briefly, it is a poor "soil", when considering nutrient and volatile resources. Instead, it is dominated by oxygen compounds (41-45%), silica, aluminium, iron, magnesium and titanium; free aluminium concentration is actually high enough to induce phytotoxic/inhibitory effects in plant growth experiments on Lunar regolith simulant [3 - 5].

The bottom line is that the Moon is an unpleasant and hostile place. What is to be done?

To start with, the Moon already offers huge sheltered spaces, adequate for early colonization. We are talking about lava tubes, already mentioned in Chapter 4. Unlike their terrestrial and Martian equivalents, low gravity causes Lunar tubes to reach absolutely astonishing sizes. Kilometer-wide ones seem to be widespread, while some even reach tens and even hundreds of kilometers in length [6, 7].

Many of the ones detected until now have collapsed ceilings, but there are clues that such natural megastructures can be stable and keep their initial shape [8].

Such formations could provide an environment sheltered from extreme temperatures and radiation, where the first permanent settlements should be built. And as you can observe (Fig. **6.2**), they would also provide enormous spaces, enough for the future colonists to build entire cities and all the needed infrastructure.

But what about the surface? Considering the differences in gravitational acceleration, respectively in area, in order to have the same atmospheric pressure as on Earth, the atmosphere’s mass needs to be 2.235 times lower, meaning 2.3×10^{18} kg.

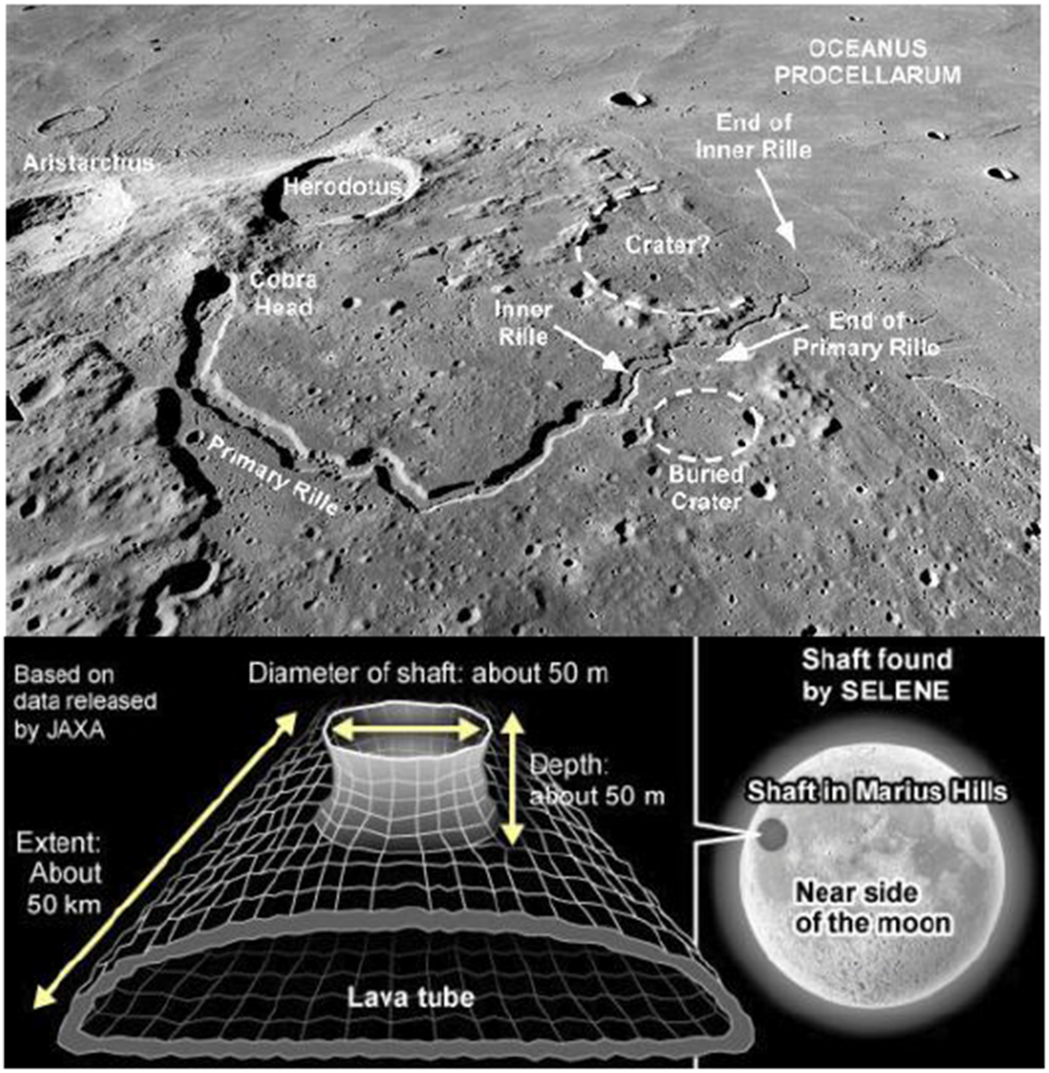

Fig. (6.2). Lava tube system (with the collapsed ceiling) on the Moon [6]; complete lava tube discovered by the Japan Aerospace Exploration Agency [7].

According to the aforementioned estimates (Table **4.1**), the lower limits for human habitability would be half of this value, meaning around 10^{18} kg. The minimum value that would stabilize atmospheric erosion somewhere around 100 kg/s would be just 10^{8} kg (10,000 times the current mass). At 10^{18} kg, the Lunar atmosphere would not be completely eroded until 300 million years from now [9].

But, it will not be eroded. We already saw how to produce an artificial planetary magnetosphere, and this would be, probably, one of the first steps to follow: installing a superconductive grid on the ground.

The main method proposed for terraforming the Moon is importing volatiles (water, nitrogen, carbon dioxide/methane) either from the Outer Solar System or from the Jovian and Saturnian Systems. It is estimated that we would need to transport a remarkably high quantity of ice, but it is not impossible to accomplish. We are talking about the equivalent of 3,000 large comets, like Halley's, or smaller comets [10].

There are numerous sources to choose from. For example, just the ring systems of Saturn contain 15 times more volatiles than needed to build up Moon's atmosphere [11]! There is also Titan, as a nitrogen source, or Venus, as a source of CO_2.

Such controlled impacts would also have the collateral effect of releasing water from the regolith and gradually changing the Moon's rotation speed [10, 12]. Furthermore, bringing asteroids to the Moon's orbit would also be the next step to building the Dyson spin motor and steadily remediating the slow rotation of our satellite (see Subchapter **5.3** and Fig. **5.10**).

But there is also a possible gradual approach. Since 2015, under NASA's Innovative Advanced Concepts (NIAC) program, scientists have been studying a technical solution for a "local terraformation". The TransFormer project envisions swarms of robots, each carrying foldable mirrors of over 40 m in diameter (Fig. **6.3**). Reflecting and concentrating sunlight towards the bottom of Lunar craters would allow installing photovoltaic equipment, creating a warmer local climate and sublimating water reserves. The first target would be Shackleton Crater, 337 km^2 in area, in the water-rich southern polar region [13, 14].

It would be the first phase of a process called *paraterraformation*, meaning partial, "under the dome", terraforming. Craters can be isolated from the outer, hostile environment by using a revolutionary material: aerogel. Silicon dioxide-based aerogel is an extremely porous material, containing over 98% air. Thus, it is extremely light, does not require vast amounts of resources to produce, can be assembled in many different shapes and ensures good thermal insulation.

It was proven that a layer just 2-3 cm thick can block damaging radiation and maintain a permanent greenhouse effect, warming the encapsulated area to above 0°C and allowing photosynthesis [15].

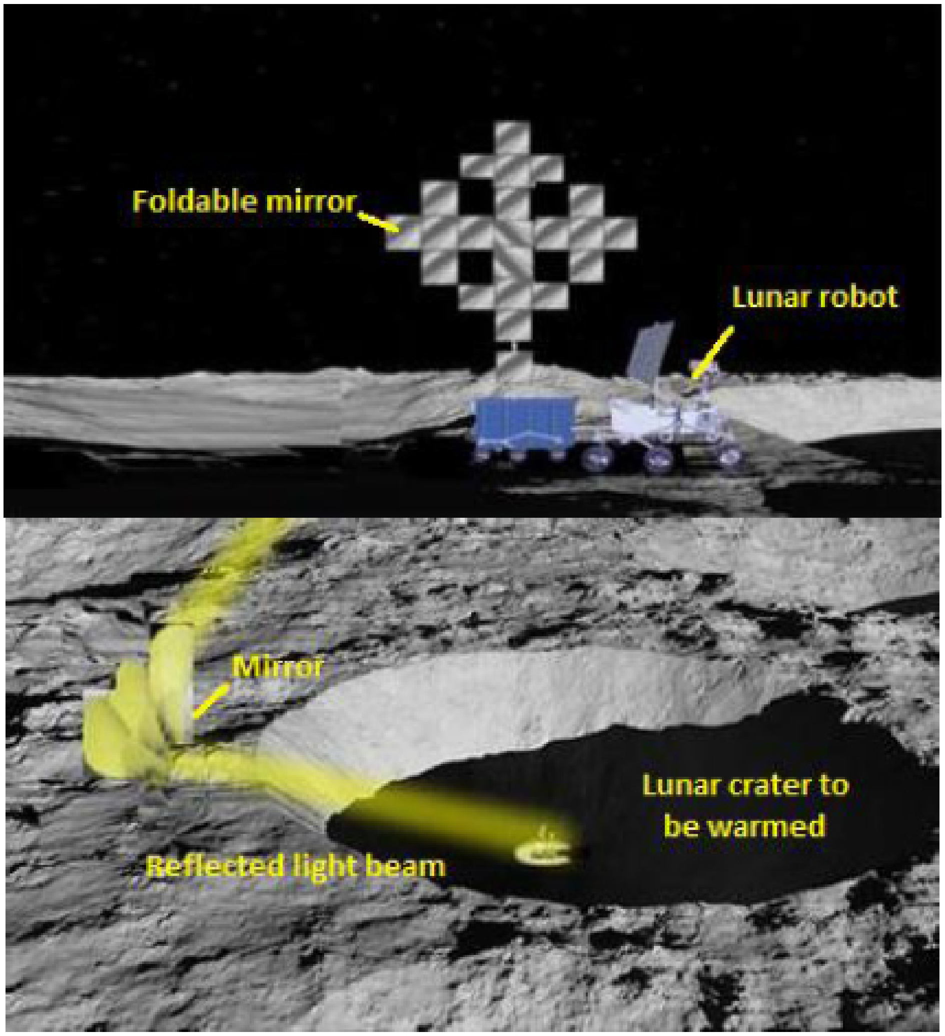

Fig. (6.3). TransFormer Project: robots carrying mobile and foldable mirrors for warming Lunar craters [13].

As rectangular or dish-shaped plates, aerogel could be used to build the outer shell of Antarctic or desert greenhouses and settlements, of future Martian or Lunar agro-industrial colonies. In the two latter cases, we can take advantage of the local rugged terrain, meaning that we could simply erect transparent ceilings over craters of various sizes [16].

As we saw in Subchapter **4.2** and Fig. (**4.7**), terraforming can also be done one step at a time, one creator at a time and even seeding with life every minor indentation of the regolith.

Yet, if on Mars, covering and heating the regolith is enough to create a mini-atmosphere, through sublimating gas reserves, on the Moon, things seem to be quite different at first glance.

Here, merely increasing temperatures above the freezing point might not release much volatiles. But Lunar regolith has an extremely interesting characteristic: due to the presence of iron nanoparticles and other similar constituents, it has a high microwave conductivity.

If the regolith is heated to 1,200-1,500°C, by using microwave generators, it quickly "melts", releasing water and other volatile compounds. It can even be done in a regular microwave oven [17]!

The beauty of this method resides in having multiple simultaneous applications. Molten and resolidified through cooling, it is a fine building material for local colonists. The process also releases almost the entire quantity of adsorbed hydrogen and helium, so it provides potential fuel.

After just 5 minutes, more than 85% of the water amount inside is turned into vapor, and if exposure continues, the percentage increases. Water can then be collected, condensed (99% of it), and used for drinking, agriculture, industry, *etc.,* Or, it can be dissociated, forming oxygen.

Finally, much of the carbon, nitrogen and sulfur content is volatilised, as CO, N_2 and H_2S. Of course, since the total amount of nitrogen seems to be below 0.25%, while that of carbon is below 0.4%, the regolith can provide atmospheric gases for a small-scale terraformation, but at a planetary scale, we might still need to import them from elsewhere [18, 19].

This method could fill with atmospheres various enclosed spaces, such as aerogel-covered craters or closed lava tubes. And a small increase in the atmosphere's mass (up to 108 kg) would shield against micrometeorite impacts [9]. Add a magnetosphere and accelerate the day-night cycle. All these will not make the Moon habitable but will allow the permanent colonization of rather vast spaces beneath and above its surface.

In the meantime, humankind should deal with the rest of the Moon's surface. Gradually, water, ammonia, CO_2, methane, *etc.*, would arrive from the rest of the System. And we can also imagine hordes of robots roaming around the Lunar fields and "bombing" regolith strips with microwaves (Fig. **6.4**).

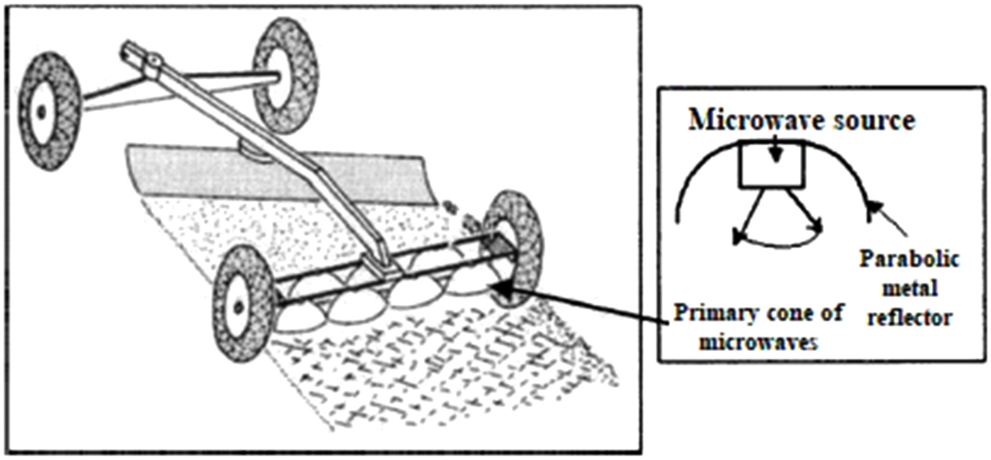

Fig. (6.4). A design of an automated device for melting and degassing surficial Lunar regolith [17].

Among the factors that could really help us, even since the beginning, is the helioformation of Jupiter and Saturn (see Chapter 5). First of all, the Moon would instantly get a more susbtantial atmosphere: 0.76×10^{15} kg of hydrogen. Then, the hydrogen wave hitting the Moon would have thousands of degrees, instantly heating and degassing the regolith. Only the first upper 10 cm would release $51\text{-}235\times10^{13}$ kg H_2O. It is just a fraction of the final target, but it is a start, allowing the human settlers to do the rest [20].

But the Moon has another potential surprise for us. As we saw, volatile reserves in the regolith are easy to release at high temperatures. Such instability can also be exploited in a much more explosive way.

Strong initial heating could release large amounts of oxygen and hydrogen, elements that are rather abundant, as we saw above. If the heating is strong and persistent enough, at over 570°C, the two gases violently react, forming water. The reaction is extremely exothermic, generating total energy of 120 MJ/kg, equivalent to a 4 MW power released in 30 seconds and raising the surrounding temperature up to 2,800°C.

But high temperatures lead to the release of new amounts of oxygen and hydrogen and new exothermic reactions. Normally, the reaction should finally dissipate at one point. But, what happens if the initial energy source is a huge one? Something like a thermonuclear blast?

Some Moon terraforming advocates put forward a simple and fast solution: several nuclear warheads placed at regular intervals around the satellite and simultaneously detonated. The thermal waves could manage to degas enormous amounts of regolith on (almost) all the Lunar surface [21].

Attention: such a method should be tried during the first stages of colonization, before building any significant infrastructure and settling! The human (and non-human) inhabitants of the Moon will not appreciate being burnt alive, along with the regolith!

Once the atmosphere and hydrosphere are created, the following steps are similar to those on Mars and the icy worlds. It would basically be a planet that slowly warms, but with much more oxygen in the atmosphere.

So, cyanobacteria and algae, lichens *etc.*, with the possibility of building up proper trophic chains even since the first stages. A process that could take less time than on Mars, even though it would lead to a less rich biosphere (Fig. **6.5**).

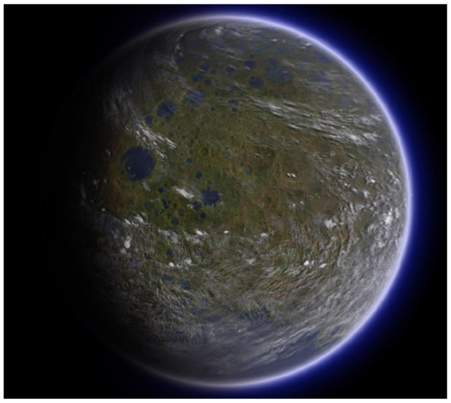

Fig. (6.5). Artistic simulation of a terraformed Moon [12].

Fig. (6.6). A terraformed Moon rises above Manhattan [22].

The Moon will probably never be a celestial body covered with extended oceans, seas, dense forests, and jungles. Yet, with some synergistic efforts, it could become a welcoming home, even though a bit arid, with a plethora of lakes within the former craters, deserts, steppes and crop fields. With billions of humans and a powerful mining, energy and space industry (due to its low gravity).

A wonderful place to walk in microgravity and a pleasant view for earthlings (Fig. **6.6**).

6.2. THE LITTLE MESSENGER

There is a small planet at less than 60 million km from the Sun (0.387 astronomical units, but with a very eccentric orbit). With a diameter equal to 0.38 Earth diameters, an area equal to just 0.147 terrestrial surfaces and gravity of 0.38 g. Basically, the smaller and denser equivalent of Mars. But with an extremely slow rotation (a day lasts for 58 Earth days), a negligible atmosphere and extreme temperatures (from -173 to 427°C). A surface constantly hit by tremendous amounts of radiation and solar wind and hostile to life (Fig. **6.7**) [2].

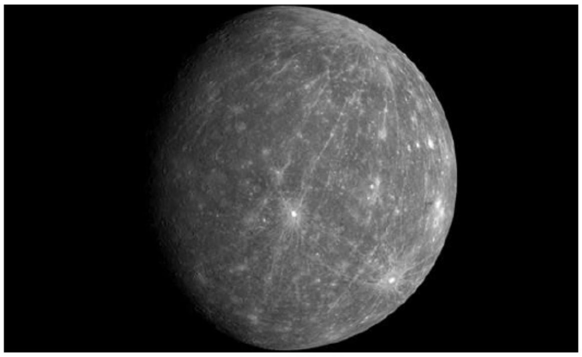

Fig. (6.7). Planet Mercury as seen from orbit [23].

It is, of course, the planet christened after the small, winged god of commerce and divine messenger, Mercury.

Even its mineral composition is an "exotic" one. Even though it has a massive iron core, the crust seems mostly dominated by alkaline and alkaline-earth metals. The main chemical elements forming surface minerals are oxygen (almost 40%), silicon (over 28%), magnesium (12.44%), aluminium (7.79%), calcium (4.55%), sodium (2.83%), sulfur, along with small amounts of iron, titanium, potassium *etc.,* Add somewhere around 10^{14}-10^{15} kg of water, under the form of a compact ice layer in polar regions. A bit of carbon, mostly as graphite (of meteoritic origin) and very little nitrogen [22 - 24].

A strange and interesting world, no doubt about it, mostly from the point of view of the mining industry. But could it become a new home for humankind?

Until now, we have some technical solutions to create a magnetosphere. Actually, Mercury already has one, equal to 1.1% of the terrestrial one, far from being enough, especially at this close distance from the Sun.

Also, even though more difficult, we can alter Mercury's rotation rate, through controlled impacts and building a Dyson spin motor (see Subchapter **5.3**).

The issue of extreme temperatures is closely connected to that of building an atmosphere. The same goes for creating a self-sustaining biosphere. But how to accomplish that when the basic bricks of life, carbon, nitrogen, and water, seem to be insufficient?

Considering the differences in terms of surface and gravity, in order to create an atmospheric pressure similar to the one on Earth, we need around 1.99×10^{18} kg of gases. For the minimum pressure needed to support human life, just about 10^{18} kg, thus a situation resembling that of the Moon.

And there is, obviously, the need for water: 10^{20} kg, for an oceanic mass similar to the terrestrial one, 1.6×10^{19} kg for a Global equivalent layer of 500 m and around 2×10^{18} for a leverage layer of 70 m, the minimum value considered to support a stable biosphere (see Chapter 4).

Of course, there is always the option of paraterraformation. Mercury has craters, of meteoritic or volcanic origin and, very likely, lava tubes (its crust is rather geologically inactive and volcanism lacks the eruptive form familiar to us, but rather slow lava flows on the surface) [25].

For some authors, Mercury is destined to remain forever a world of paraterraforming, of limited habitability, in subterranean settlements or beneath aerogel domes [26].

If we want more than this, we need to import the necessary volatiles on a large scale. Just like in the Moon's case, we are talking about tens of thousands of comets and iceteroids. It is true that the Solar System, as discussed above, hosts huge amounts, even if we only consider the small objects that form the rings around the gas giants.

Carbon dioxide and nitrogen can also be imported from Venus or Titan. The problem is not that we might "overuse" these two bodies by transporting their nitrogen to multiple areas of the Solar System. The atmosphere of Venus contains 3.5% nitrogen, which, considering the total mass, means four times more than

Earth's atmosphere. So, more than enough to terraform Venus and three more planets!

But, as we saw, even with massive ballistic capacities, we would need millennia to ship the entire amount needed.

For such cases, there is still a solution: confined atmospheres.

Let's imagine that we could stretch a "membrane" over the planet, at the height of around 3,000 m (higher than most mountains on Mercury)! The mass needed to build the atmosphere would drop to just 12.4% of the initial one. This is because the membrane limits atmospheric volume, maintaining the same pressure instead.

At the height of 1,000 m, only 4.3% of the total mass would be needed. Thus, somewhere between 4-8×10^{16} kg. Instead of 10,000 average comets, we would just need some 400. Not really a piece of cake, but it is a major difference!

To withstand the gravitational force, it is estimated that such a membrane should be about 3 m thick, if we choose steel as the building material (at 3 km of altitude; this value increases towards the surface and decreases at higher altitudes) [27].

But, of course, it is not necessary to use steel for the entire structure. Nor desirable since settling the planet also requires sunlight.

In the previous subchapter, we have already presented an extremely valuable material: aerogel. Being composed of over 98-99% air, it can be easily kept in place at a certain altitude, with a minimal metallic grid.

One of the lightest silica aerogel types has a density of 3×10^{-6} kg/m^3, although there is a graphene-based version that is 6 times lighter (and also 3D-printable: 0.5×10^{-6} kg/m^3) [28, 29].

At a thickness of 1 m, such a planetary membrane would weigh around 22.5×10^7 kg, if we choose the silica option (silica is much more abundant in surface rocks on Mercury), or 3.75×10^7 kg, if we use graphene (the raw material, carbon is also present on Mercury and can also be mined from asteroids). We are talking of 37,500-225,000 tons. There are currently oil tankers heavier than that!

How could such a construction proceed? We should probably start by building some orbital ring systems (see Subchapter **3.1**). Their altitude would be too elevated for the membrane to start directly from the rings, but they would allow optimal transportation of necessary resources and an orbital infrastructure would be more suitable for the mass production of aerogel panels.

The following step is erecting towers of the desired height. Of course, at 1 km altitude, such towers would be taller than the Burj Khalifa, but we would actually need just some tall pillars, not proper buildings (and low gravity would help us a lot). Starting from the support pillars of orbital rings, we could create longitudinal and latitudinal arrays of such structures.

Then, we connect them at high altitudes through cables and begin placing the aerogel panels and starting from the Equator, where the escape velocity of gases is higher. Once we "fill" the whole atmosphere with imported volatiles, the membrane would close over the polar regions, too.

This way, Mercury would get an atmosphere while continuing to receive sunlight. But, can we do more than that?

Let's take a look deep inside the planet! Where does Earth's atmosphere come from? From the mantle, of course, continuous ancient eruptions released the constituent gases. Surely, the origin is much more complex, involving ice asteroid/cometary showers or massive impacts, during the stages that preceded solidification, but the main idea is that Earth's mantle contains major reserves of water (up to 77% of the total water amount on the planet!), carbon dioxide (12%), nitrogen, sulfur oxides *etc.,* [30, 31]

Mercury was also subjected, during its first stages of existence, to massive impacts that caused it to lose the external layers of the mantle, while very likely retaining significant amounts of volatiles [32].

We do not know yet what is the exact chemical composition of Mercury's mantle, but there are models that indicate an enormous amount of carbon, for instance, forming a continuous layer beneath the current crust (practically, the planet's primary crust was dominated by graphite!) [33]. Other valuable elements also seem to be abundant. Thus, chemico-mathematical modelling indicates, as the main probable volcanic gases, N_2, CO, S_2, CS_2, S_2Cl, Cl, Cl_2 and COS [34].

But volcanism on Mercury is very slow. So, how could we degas the planetary mantle? Easy: by using controlled asteroid impacts, as we already discussed in Subchapter **4.1**. We already saw the solution by Orme and Ness to quickly terraform Mars by hitting the planet with a metallic asteroid, measuring some hundreds of kilometers in diameter, to trigger a volcanogenic greenhouse effect [35].

On Mercury, we must do more than that: an extremely intense volcanism is needed, with large regions of the exposed mantle and massive lava flows. We must pierce the planet's lithosphere over vast areas.

And fortunately, the structure of Mercury helps us a lot. Its crust has an average thickness of just 26 km (±11 km)! One of the thinnest known lithospheres [36].

An impact with an object ten kilometers wide would undoubtedly make a big hole. Let's take, for instance, a few small icy moons in the Solar System!

Belinda, Caliban, Sycorax, and Setebos, are all minor satellites of Uranus. Sycorax is the most massive of all, with 157 km in diameter. If the effort required to move it out of orbit is too great, Caliban is only 42 km wide. They are located more than 7 million kilometers from Uranus, so they are relatively easy to extract from its gravitational field.

And most of their mass (0.25×10^{18} kg, for Caliban, about ten times the amount, if you choose its big brother) is made up of water ice. Spectral analyses indicate a most likely composite structure, with interposed fragments of rock and ice [37].

By using gravity assist, gravity-powered traction and/or NERVA thrusters (water is easy to vaporize and use as fuel), we could dislodge such a body from its orbit and divert it towards Mercury. Any of them would create a huge crater in the planet's 26 km thick crust.

At a velocity similar to the current one, crashing Caliban would release energy of 1.69×10^{25} J (almost 6 times higher for Sycorax). Even at a lower velocity, any of these objects would cause a tremendous blast.

The Chicxulub crater, in Mexico, covering an area of 25.000 km^2, with a maximum depth of 20 km, was caused by an asteroid or comet having a diameter anywhere between 10-80 km (thus, about the size and mass of Caliban), releasing total energy of 10^{24}-10^{25} J [38]. And, at such a thin crust, the impact could easily reach the mantle especially if we consider the composition of local rocks.

Let's assume energy equal only one-tenth of the aforementioned one! 1.69×10^{24} J would be enough to vaporize around 2×10^{17} kg of MgO (the easiest to vaporize of all the compounds in Mercury's crust, with 330 kJ/mol heat of vaporization) [39].

MgO forms one-quarter of the total mass of crustal rocks, meaning that 8×10^{17} kg of the lithosphere would simply blow up [40].

At some 2,974 kg/m^3 average density and 26 km crustal depth [36], this means the equivalent of a 10,000 km^2 lithospheric surface, as a minimum value! A "hole" in the crust having roughly the size of Lebanon. At higher energy, around 10^{24} J, the "exposed" area would be equal to half of the entire surface of Romania!

Such impacts would perform multiple functions. Opening up the mantle and gas emission (thus providing a source of carbon and nitrogen), water (and carbon dioxide, ammonia) input would also support the gradual change in the planet's day-night cycle.

However, there is some bad news: due to the high reactivity of crustal oxides, part of the water imported on the planet would be consumed by hydrating its surficial layers, forming calcium and magnesium hydroxides. Hydroxides, in turn, would gradually get carbonated, thus releasing water but consuming some of the carbon dioxide provided by the mantle and that imported from other regions of the Solar System, meaning that higher amounts of both compounds would be required.

Even more, these reactions are exothermic, generating 65 kJ/mol CaO [41], respectively 81 kJ/mol MgO [42].

For this reason, but also for the obvious one of being close to the Sun, once the atmosphere and hydrosphere are created, the main problem remaining is how to cool them. Currently, the average temperature is around 167°C.

There are two known cases of the planetary-scale anti-greenhouse effect.

Titan keeps its surface temperature 9°C lower than predicted. This is due to photochemical reactions involving methane molecules in the upper layers of the atmosphere. Under ultraviolet radiation, a dense "haze" made up of ethane and acetylene is formed, blocking the absorption of about 90% of incident light, while also not reflecting infrared radiation from the moon's surface [43].

The second case is that of Venus. Venus is a real hellish world, with an average temperature of 462°C, caused by enormous amounts of carbon dioxide. Still, temperatures are somewhat kept stable by the presence of sulfur dioxide (SO_2). Once it reaches the upper atmosphere, it is photo-oxidized to SO_3 and then it reacts with water vapor, forming compact clouds of sulfuric acid, extremely reflectant, especially if they also contain various impurities [44].

This is roughly what happens here, on Earth, following volcanic eruptions. And what could happen on Mercury, too, following controlled impacts and degassing of the mantle.

The long-term result of asteroid "bombing" and volatile import will be a progressively thicker atmosphere, dominated by nitrogen, carbon dioxide and water vapor (also with elevated levels of sulfur oxides). After a few impacts with objects having the size and composition of Sycorax, the amount of water would be large enough to generate a limited hydrosphere.

Global cooling and growing pressure would result in large bodies of liquid water, an acidic one, due to carbon and sulfur oxides. Carbonate and sulfate deposits would form. And at temperatures that allow liquid water, life could start settling.

And life should start with photosynthetic organisms, able to consume excess CO_2 and generate a breathable, earthlike atmosphere. Unlike all the other planets discussed in the previous chapters, now we are talking about a cooling planet.

Pioneer organisms, in this case, should be thermophilic but also able to withstand hypoxia and an oscillating pH (alkaline, in the beginning, due to hydroxides in the upper planetary crust, but becoming more and more acidic, once atmospheric carbon and sulfur oxides start dissolving into water bodies).

The most thermophilic cyanobacteria can live and keep an active metabolism at temperatures up to 74°C. We are mainly talking about the genera *Synechococcus* (especially *S. lividus*) and *Thermosynechococcus*, which are common in thermal springs worldwide (Fig. **6.8**).

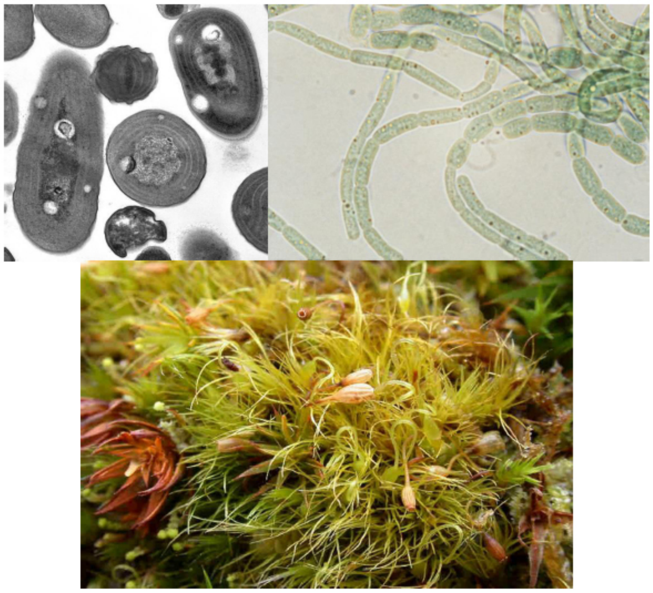

Fig. (6.8). Pioneer-species useful in terraforming Mercury (and other hot worlds): *Synechococcus* sp [45], *Mastigocladus laminosus* [46], *Campylopus pyriformis* [47].

One step lower, we find some thermophilic species belonging to the genera *Mastigocladus*, *Phormidium*, *Oscillatoria*, *Phormidium*, *Chlorogloepsis*, *Leptolyngbia*, or the calciphilic species *Gloeomargarita lithophora*, with a tolerance up to 55-64°C.

Then, between 45-50°C, there are species of *Synechocystis*, *Gloeocapsa*, *Gloeocapsopsis*, *Symploca*, *Stigonema*, *Fischerella*, *Plectonema*, *Lyngbia*, *Spirulina*, *Pleurocapsa*, *Calothrix, etc.*, [45 - 50].

While most cyanobacteria tend to prefer a neutral or alkaline pH (with a specific tolerance to elevated pH values, going up to 9-10), some species of *Oscillatoria*, *Limnothrix*, *Spirulina*, *Aphanocapsa*, *Chroococus* are acidophilic (pH 2-4).

Among eukaryotes, a primitive red alga, *Cyanidium caldarium*, like waters with temperatures between 45-57°C and a low pH (as low as 2-4), while also being able to withstand pure CO_2 atmospheres. Green algae, such as *Dunaliella acidophila* and *Chlamydomonas acidophila*, can tolerate low pH values (even below 2).

Species of *Mastigocladus* and *Chlorogloepsis* also have the useful characteristic of fixing atmospheric nitrogen [49, 51]. For eventually occurring highly saline environments created following the reactions between local mineral compounds, water and the primary atmosphere of Mercury, there are some halophilic and thermophilic (48°C) cyanobacteria in the genus *Euhalothece* [52].

Following the bacterial stage, epilithic thermophilic lichens, native to tropical regions and not only, should be introduced. Species like *Peltigera scabrosa*, *P. rufescens* or *Biatora granulosa* can withstand temperatures around 45°C, without any notable physiological effects [53].

A moss species, *Campylopus pyriformis*, impressed the scientific community after some compact communities were found growing on volcanic soils in New Zealand, having temperatures up to 72°C (Fig. **6.8**). Also, the fern *Lycopodiella cernua* and shrub *Kunzea ericoides* (Family Myrtaceae) can tolerate up to 68°C [54].

Unlike cold planets, where *Sphagnum* peat bogs could play a key role in consuming excess atmospheric CO_2, in a warm climate, this is not possible. There are, however, tropical peatlands, some of them produced by *Cladium jamaicense* and the members of Family Cyperaceae (basically, sedge species) [55].

The ecological succession would continue, somewhat according to an upside-down version of (Fig. **4.12**), from hot to cold environments. Mercury will probably remain a rather arid planet, lacking luxuriant environments, just like the Moon (Fig. **6.9**). The important thing, however, is that we could be able to transform it into a habitable world, even without forcing people to live under aerogel membranes. Or, at least, we could try.

Fig. (6.9). Artistic vision of a terraformed Mercury [56].

6.3. PEBBLES IN THE SKY

Besides the great planets, there is also a plethora of small celestial bodies – dwarf planets and various moons that orbit the gas giants.

Take Ceres, for instance (Fig. **6.10**). You could consider it a huge asteroid or a dwarf planet. It has an average diameter of 1,062 km, a mass close to 10^{21} kg and gravitational acceleration of 0.029 g. Neither Vesta (525 km in diameter, 0.025 g) nor Pallas (512 km, 0.022 g) should be neglected. They are all located at distances ranging between 2.3-2.8 astronomical units from the Sun.

You can also check (Table **4**) for some of the most important satellites of Saturn, other than Titan. Rhea (1,527 km, 0.026 g), Iapetus (1,469 km, 0.023 g), Dione (1,122 km, 0.023 g), Tethys (1,062 km, 0.014 g) sau Enceladus (513 km, 0.011 g). And I selected, somewhat arbitrarily, bodies having gravitational accelerations above 0.01 g and located at a convenient distance from their star (up to 3 AU from the Sun, respectively $0.3\text{-}3\times10^{-2}$ AU from a helioformed Saturn) [2].

Let's return to Ceres! First of all, this object is located over 2.7 AU from the Sun, meaning an amount of incident sunlight equal to 14% of the terrestrial one and a half of that on Mars. Is this enough?

We should note that here, on Earth, of the 21.6 MJ/m^2 daily incident solar energy, only around 51% reach the ground. The rest is reflected by the atmosphere (6%), clouds (20%) and planetary surface (4%), absorbed by the atmosphere (16%) and clouds (3%) or converted to thermal energy that keeps air masses moving. Of the remaining 51%, 44% are radiated back into the atmosphere. Thus, only 6% can be used by biological systems (Fig. **6.11**) [56 - 59].

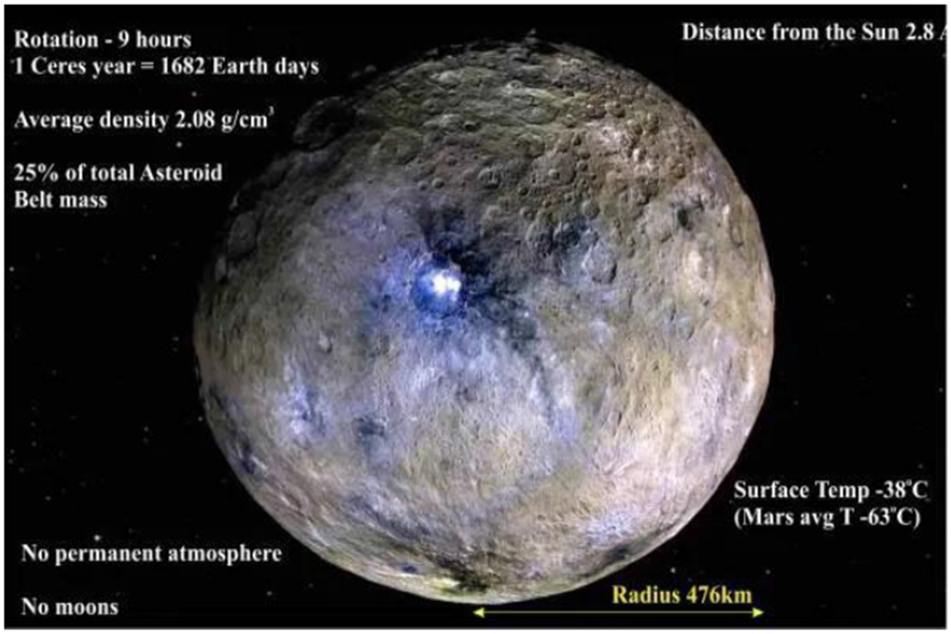
Rotation - 9 hours
1 Ceres year = 1682 Earth days
Average density 2.08 g/cm^3
25% of total Asteroid Belt mass
Distance from the Sun 2.8
Surface Temp -38°C
(Mars avg T -63°C)
No permanent atmosphere
No moons
Radius 476km

Fig. (6.10). Dwarf planet Ceres, with some of its main features [57].

So, planetary engineering can "play" with these values, by drastically lowering the planetary albedo, respectively, through a lower density of the atmosphere or strict control of clouds. Doubling the amount of usable radiation would bring Ceres to levels similar to Martian ones.

Basically, up to a point, there is a direct proportionality between incident sunlight and photosynthesis rate, which in turn, determines plant productivity.

Let's not worry, though: there are ombrophilic species on Earth, especially among those forming the lower layers of forests. Studied conducted in tropical rainforests, for instance, found that plant species such as *Varronia curassarica* or *Symphyopappus casarettoi* thrive at values as low as 18% of the normal incident radiation [60].

Even a common cactus *Opuntia ficus-indica* (chumbo, Indian fig), exhibits normal metabolic activity at 15-20% of the normal sunlight [61], and *Atriplex patula*, spear orache, can tolerate percentages around 25%, with no major effect on its physiology [62].

As for algae and other photosynthesizing micro-organisms, it is enough to mention that just 10-20% of the incident solar radiation reaches depths of 20 m, in many marine basins, without causing significant decreases in the overall density of photoautotrophic life forms [63]. Basically, astrobiologists consider the limits of oxygenic photosynthesis to range between 0.1-8 μmol photons per meter per second (some even consider a lower limit of 0.01), meaning anywhere between 5 and 800% of the sunlight that reaches Earth [64].

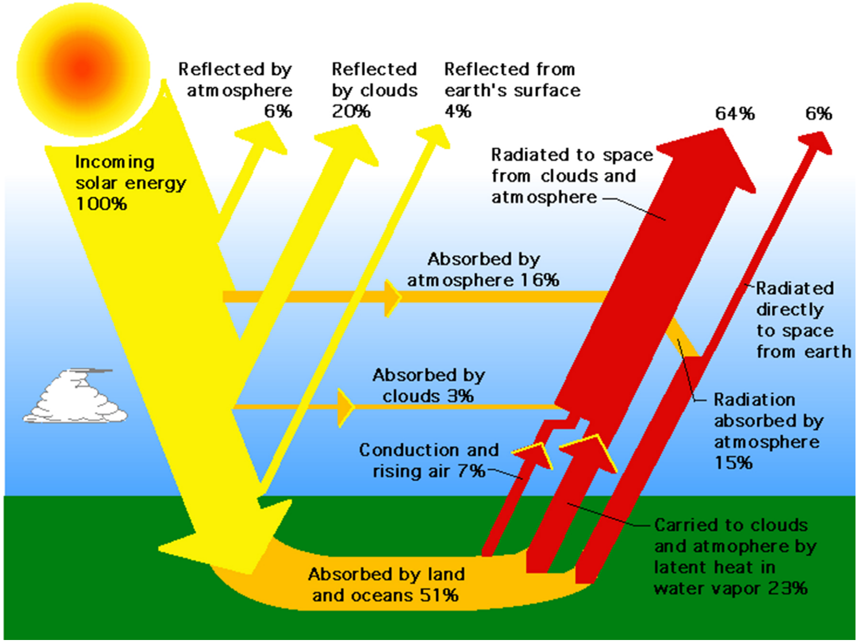
Reflected by atmosphere 6%
Reflected by clouds 20%
Reflected from earth's surface 4%
64%
6%
Incoming solar energy 100%
Radiated to space from clouds and atmosphere
Absorbed by atmosphere 16%
Radiated directly to space from earth
Absorbed by clouds 3%
Radiation absorbed by atmosphere 15%
Conduction and rising air 7%
Carried to clouds and atmophere by latent heat in water vapor 23%
Absorbed by land and oceans 51%

Fig. (6.11). Distribution of incident solar energy on Earth [59].

Anyway, Ceres has an average surface albedo six times lower than Earth, thus, a smaller proportion of the solar radiation would be reflected back to space. Proportionally, this means a direct increase of one-third of its incident sunlight, equivalent to 19-20% of the terrestrial one. Even lower than this is the albedo of Iapetus, the farthest of all the aforementioned Saturnian moons.

Albedo can be further reduced by surfacing part of the vast reserves of organic carbon found inside Ceres. We are talking about chondritic mixtures and even graphite, of dark color [65]. Another way to lower light reflection in a future, post-terraformation atmosphere is by systematically "seeding” the clouds [66] or simply building an atmosphere with a lower mass and density, as we will discuss below. Thus, none of the celestial bodies mentioned here seem to be problematic in regard to photosynthesis.

A day on Ceres lasts for nine hours, meaning there is a regular day-night cycle. If our descendants wish to slow it down, in order to bring this cycle to a length more similar to the one on Earth, they will have several technical means to accomplish this, as we already saw that the rotation bodies much larger than Ceres can be altered.

The next step is to find the resources needed to build up an atmosphere, hydrosphere and to support life.

Although located within the Main Asteroid Belt, Ceres has a structure somewhat more similar to the main moons of Jupiter and Saturn (Fig. **6.12**). The main difference is the higher percentage of rocks.

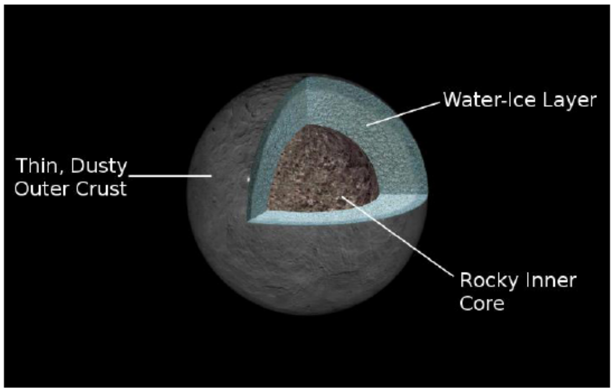

Fig. (6.12). The internal structure of Ceres [65].

Its lithosphere is 40 km thick, formed by a mixture of minerals and ice, featuring countless small-sized craters (below 280 km in diameter). A regolith covers the surface with a dusty consistency.

The abundance of hydrated minerals indicates that sometime in the distant past, ocean bodies were present. The crust also abounds in carbonates, chondritic material, graphite and amorphous carbon, all being valuable carbon sources.

Beneath the lithosphere lies a mantle (over 100 km thickness), formed of ice, possible layers of liquid water and minerals. At the center, a rocky and/or metallic core. Ceres shows phenomena of cryovolcanism, with muddy eruptions of water, ammonia and minerals. Up to 25% of the planet's total mass might be water [65, 67, 68].

Local chondritic rocks contain up to 30% water. Nitrogen is also present in some ammonia-rich clays [69].

So, what does this planet lack that prevents it from supporting life? An atmosphere.

And there are many ways to produce it. We are actually talking of a Martian-type scenario, on a smaller scale. Gradually warming the planet would release water vapor, possibly ammonia and carbon dioxide, and the resulting greenhouse effect would release new amounts of volatiles.

Considering its surface and gravity, Ceres would need an atmospheric mass five times lower than that on Earth, in order to reach the same pressure. Thus, an optimum is around 10^{18} kg, but a minimum of 0.5×1018 kg is possible.

If we consider the percentage of water to be 25% of the total mass, minus the mantle (with about 30% water), the lithosphere must have the equivalent of around 1.5×10^{20}, meaning one-tenth of the terrestrial Planetary Ocean. Around one-hundredth of the mass would be enough for an ocean of an earthlike size, while the water contained in the first 40 meters of the regolith could fuel a decent hydrosphere, with an equivalent water layer of more than 300 m. The topography of Ceres is heterogenous enough (Fig. **6.13**) to allow the existence of landmasses, with elevation differences as large as 8,000 m.

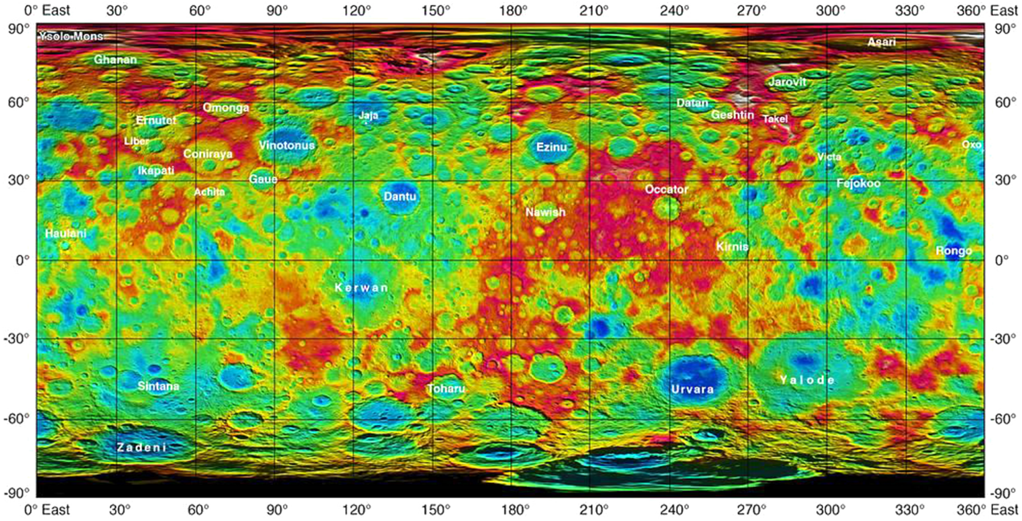

Fig. (6.13). Topographic map of Ceres [70].

Other volumes of water, equivalent to the reserves found in 200-400 m of the planetary crust, would be required to build up the atmosphere. After water vapor is photolytically dissociated, oxygen would be released [70].

Of course, this assumes that water is easily extractable from the regolith. There are some clues of shallow ice water deposits [71], but much of the water is bound to minerals, so it could be less accessible than it seems. Also, while we know there is ammonia, we do not know the exact amount.

This means that some import of volatile resources could be unavoidable after all.

Otherwise, terraforming techniques might include orbital mirrors or a slight adjustment in the planet's orbit (through gravity assist; its mass is 100 times lower than that of our Moon), bringing it closer to the Sun – which would increase the amount of incident sunlight.

Using microwaves, just like on the Moon, or controlled thermonuclear blasts, could be even more effective in degassing the regolith. The main targets of such bombings would be the so-called "bright spots", areas of low albedo that contain compact deposits of sodium carbonate. The most prominent such region is found at the bottom of the Occator crater [65].

Thus, we could mobilize large amounts of carbon dioxide, water and ammonia. Venus and the moons systems of the four giant planets could serve as sources for eventual imports. Neither the option of deep drilling through the crust nor bringing up water by mechanical means should be ignored.

We can combine various such strategies without excessive resource spending: the whole planet has a surface area about the size of Argentina!

And after a slight increase in average temperature and atmospheric pressure, the first micro-organisms will be ready to be released on the surface. Among others, nitrifying bacteria would play a key role. *Nitrosomonas* sp. and company (see Subchapter **5.2**) would transform ammonium salts into nitrates, while *Pseudomonas* sp., *Alcaligenes* sp., and other denitrifying organisms would release nitrogen oxides and dinitrogen into the atmosphere.

The bottomline is that Ceres seems to be one of the easiest terraformable worlds in the Solar System (Fig. **6.14**). With one exception: low gravity.

The gravitational acceleration of the tiny planet is equivalent to just one-fifth of the Lunar one. And the big issue here is not that taking a walk on its surface would be somewhat weird, or that microgravity has some effects on the human organism (that, as we saw, can be tackled). Neither its effects on crops, since several experiments conducted in simulated microgravity have shown there is no major hindering of plant growth up to 10^{-2} g [72].

The big issue is atmosphere retention. With an average equatorial escape velocity of 0.51 km/s, it barely surpasses the average molecular escape velocity of oxygen (0.48 km/s at 20°C) and nitrogen (0.50 km/s), which is extremely problematic, even if we build an artificial magnetosphere.

The atmosphere would simply be eroded over time. It would probably last for tens of millions of years, but it would require a refill at one point. And, even if there are major water reserves in the lithosphere and mantle, plus various sources for other volatiles, sometime in the far future, we might find out that maintaining an atmosphere on a fully terraformed dwarf planet is just too expensive.

So, little Ceres might need paraterraforming after all. It should start from the plethora of surface craters, among the largest being Occator, Yerwan and Kalode [73].

And then, we should gradually cover the entire planet. We saw that 37,500-225,000 tons of aerogel are enough to completely enclose Mercury. At an area 27 times smaller, Ceres would only need some 1,400-8,300 tons. An easily accessible mass, once we manage to erect the support pillars, and build silicate processing and 3D printing facilities.

Vesta, Pallas, Hygiea and other smaller asteroids are even more difficult to "tame". We know that Vesta (the most thoroughly studied and, somehow, the standard for this class of bodies) has a predominantly chondritic crust, with large amounts of water and organic compounds. We also know that there are some hydrated minerals and, very likely, ice deposits within the regolith. The inside, however, looks rather like that of telluric planets: a thick, rocky crust, probably with much less water than that on Ceres and a mantle made of magma [74 - 76].

In this case, volatiles can be imported from elsewhere, but low gravity makes such bodies more suitable for paraterraforming.

As for the smaller moons of Saturn, their evolution following helioformation will depend on their degree of internal stratification, yet insufficiently known. Weakly stratified moons, with inner structures more similar to that of Callisto, Ganymede or Titan, can maintain some landmasses after the lithospheric ice melts. This seems to be the case with Iapetus [78] and even Dione, where a (more or less) homogenous crust is 100 km thick [79].

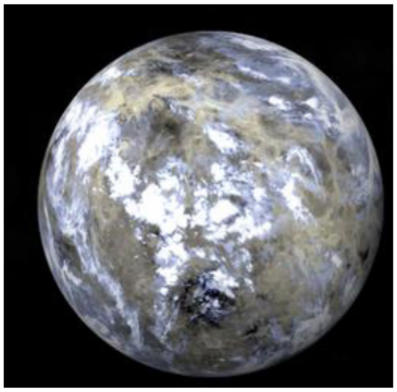

Fig. (6.14). Artistic vision of a fully terraformed dwarf planet Ceres [77].

An entirely different situation is that of worlds having a strong internal layering and/or thin crust, especially if they are located close to the helioformed gas giant. Although there are various estimates of the lithospheric thickness on Enceladus, going up to about 96 km [80], most models imply a crust formed (almost) entirely of ice, with a 20-50 km thickness [81]. The same goes for Mimas, whose composition seems to be dominated by water, in all its forms [82].

Such objects would melt entirely. A bit like in the post-apocalyptic movie "*Waterworld*", but even more unpleasant: the bottom of the ocean would lie hundreds of kilometers below, with no island to shelter the colonists. This does not mean that such worlds are uninhabitable, just that there are some major issues.

Such moons, having excess water, should probably be moved to more distant orbits, where temperatures could be kept around the freezing point. How can we move planets and planetoids? We will find out in the following chapter.

Finally, paraterraformation seems to be the solution for all these moons, due to their low gravity. We saw that it is possible: land areas covered by aerogel domes, integral planetary domes or, on worlds kept cold, underground settlements with confined atmospheres.

These are the means that might make even the funny Mimas, with its shape that "*Star Wars*" fans will find very familiar (Fig. **6.15**), able to host millions of inhabitants.

For even smaller moons and asteroids, there is the option of excavating them and either building sheltered habitats under transparent domes or giving them a suitable rotation in order to create, using the centrifugal forces, simulated gravity conditions inside their internal cavities.

We are talking about *O'Neill habitats*. First imagined in the '70s, by Gerard O'Neill, this concept initially involved massive, cylindrical orbital stations, with a continuous rotation that ensures simulated gravity inside them [83].

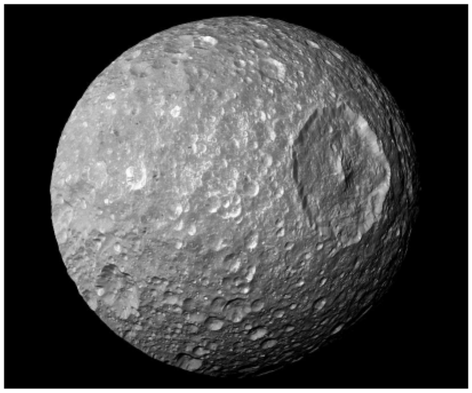

Fig. (6.15). Mimas: one of the possible candidates for paraterraforming [82]?

Then, a wide variety of versions of these huge, kilometers-wide colonies, were put forward: toroidal structures, complexes of cylinders or tori *etc.,* Not that such a structure was ever built, due to a simple reason: for the moment, transporting and assembling such objects into orbit have prohibitive costs (see Subchapter **3.1**) [84].

And, most likely, even with all the future technological progress, building O'Neill habitats from scratch will never be affordable. But why build from scratch when space provides us with plenty of building materials? Hundreds and hundreds of asteroids, several kilometers in diameter, plus tens of minor moons around Jupiter and Saturn (and even Deimos and Phobos, the tiny satellites orbiting Mars), can serve as bases to build such structures.

Basically, we are talking about underground cities that are excavated inside these celestial bodies. While in the collective imaginary and SF literature, there is usually a single, huge, central cavity, for efficiency and security reasons, several interconnected cavities would be more feasible.

It is the same principle as that behind domed settlements and the paraterraforming concept, just that their inhabitants will stand with their feet oriented towards the exterior, due to the simulated gravity.

Otherwise, transparent "windows" should also be present in this case, along with some sunlight-reflecting and transmitting systems (see Subchapter **2.2**). Cavities should contain atmospheric gases, in breathable proportions and at adequate temperatures, amounts of liquid water, plus micro- and macroscopic life forms, that would produce soil and food, while also maintaining the atmosphere within optimal parameters (Fig. **6.16**).

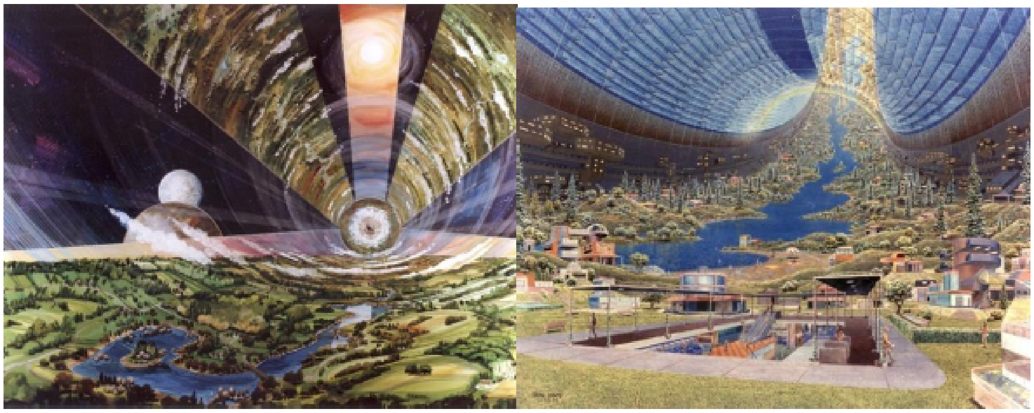

Fig. (6.16). Inside views of some O'Neill habitats: cylindrical and toroidal versions [84].

Icy moons and asteroids with elevated water and organic matter contents would be the most suitable for such habitats (and also easier to dig). Our only major contribution will be to give them an adequate rotation speed, through gravity assist/traction, rocket engines, mass drivers, *etc.*

A celestial body, 10 km in diameter, should rotate 0.4 times a minute, for a 1 g gravity (0.26 rotations per minute for a Mars-like gravity, 0.17 for a Moonlike one).

A body 100 km wide needs 0.13 rpm for 1 g, 0.055 rpm for a Moonlike gravity (equivalent to 1,000 km/h tangential speed) Of course, even 0.055 rpm, meaning 79 rotations a day, is a much higher speed than that of the vast majority of objects found in the Solar System and would generate a bizarre day-night cycle, but humans, animals and plants could easily accommodate, as long as the lighting level is proper.

I will let you calculate different rotation scenarios for various bodies and gravity levels: just follow the link attached to this citation [85]!

And, when life science and engineering work together, possibilities are limitless. Even the smallest, farthest and coldest moons and iceteroids could harbor "air pockets" (naturally occurring or man-made) within their ice crusts that, with adequate heating, lighting and seeding, will allow the creation of new unique habitats [86].

Other envisioned projects take space mining and construction to another level. Prof. Pekka Janhunen (from the Finnish Meteorological Institute, also advising several aerospace enterprises) proposes using building materials and volatiles from Ceres to build a disk-shaped megahabitat, formed of thousands of interconnected, 10 km-long, rotating O'Neill cylinders, each providing 1 g artificial gravity, in the dwarf planet's orbit, taking advantage of this body's low gravitational pull [87].

While Ceres, as we saw, might be more suitable for actual terraformation, such artificial orbital habitats might be an option for Vesta, Pallas, or other small and inhospitable celestial bodies.

CONCLUSION

Even the smallest celestial bodies can be turned into abodes for human and non-human life.

Nuclear blasts and microwave sintering could render the Moon (or, at least, large parts of it) habitable. For Mercury, the most effective solution could be trigerring massive, directed asteroidal impacts, in order to degas its mantle, while thermophilic microbes and plants should do the rest. For Ceres, we should use the same means as on Mars to warm the crust and release volatiles through a positive feedback loop.

Other objects in the Main Asteroid Belt would probably require importing volatile resources elsewhere. Smaller moons around the gas giants would naturally warm up and degas after helioforming Jupiter and Saturn.

Paraterraforming is a reasonable way of action when it comes to colonizing bodies with low gravity. It allows keeping the atmosphere on a very long term and lowers the demand for volatile resources to achieve a decent pressure. Aerogels – novel light and transparent materials – might prove to be the key to accomplishing this.

For even smaller planetoids and moons, there is always the option of excavating them and creating habitable spaces inside.

Since there are a large number of such objects in the Solar System, pursuing such strategies could create an enormous total living space, hosting billions or tens of billions of people and greatly expanding our civilization.

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CHAPTER 7

A World of Fire

Sometimes, to win you must know how to wait.
Getúlio Dornelles Vargas

Abstract:

Although our planet's "twin" in any other aspect and object of several terraformation scenarios, Venus is a very difficult target for human settlement. Due to its extreme atmospheric pressure and temperature, it is the most inhospitable celestial body in our Solar System.

This does not mean that terraforming it cannot be done, but in order to do it in a reasonable time, some technologies that are currently out of our reach need to be applied. Wormholes are the best option, coupled with some large-scale megastructure buildings, plus "regular" planetary engineering means. Fortunately, even if it seems like SF, scientists are currently making serious advances towards achieving such technologies.

At the end of the process, Venus could be transformed into the most habitable world in our System, a true paradise.

Keywords: Atmosphere removal, Planetary cooling, Sunshades, Terraformation, Venus, Wormholes.

The Latin goddess of beauty, love, fertility and abundance, represented as a gorgeous, but also difficult and moody woman; neither less beautiful nor less difficult is the planet christened after her. We are, of course, talking about Venus, Earth's "twin sister" (Fig. **7.1**) [1].

It has a diameter equivalent to 94% of Earth's, a mass of 81.5% and a gravitational acceleration of 0.9 g. It is located at 0.7 AU from the Sun, and a Venusian year lasts for 224 terrestrial days [2].

It seems that the planet had a pleasant climate for over two billion years, with a reasonable atmosphere and, maybe, oceans and other bodies of liquid water. Then, 715 million years ago, Venus underwent dramatic changes.

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There are various explanations: the Sun-Venus relation, crust and mantle features, that prevent CO_2 sequestration, tidal phenomena or a major impact (maybe with its own moon), melting part of the crust and causing chaotic volcanism [3 - 6].

Fig. (7.1). Venus as seen from orbit; in reality, the planets's surface is difficult to observe, due to its dense atmosphere and opaque clouds [1].

No matter what the actual mechanism was, it led to an accumulation of huge amounts of gas in the atmosphere, and the planet literally turned into hell! The atmosphere reached a pressure of 9.2-9.3 MPa (92-93 times higher than the terrestrial one, of which 3.5% is nitrogen and the rest CO_2). The average temperature on the ground currently reaches 464°C! It is quite reliable proof that carbon dioxide has a greenhouse effect and that maybe we should refrain from raising its concentration in Earth's atmosphere!

All water bodies on the planet boiled a long time ago, generating, by reaction with sulfur oxides, bizarre clouds made of sulfuric acid, reflecting around 75% of the incident sunlight but without managing to quench the greenhouse effect [7].

The same apocalyptic event probably changed the rotation speed and direction: Venus has a retrograde spin, lasting for 243 Earth days (a Venusian day is, literally, longer than the year!).

Maybe you wonder why I never mentioned this planet until Chapter 7. Usually, in all terraforming papers, it comes second. But considering the environmental conditions (extreme temperature and pressure, no water, rotation rate), you will agree that Venus is a hard nut to crack.

7.1. HOW TO GET RID OF AN ATMOSPHERE?

It is obvious that the main obstacle preventing habitability on Venus is its enormous atmosphere. Contrary to the Martian case, less atmospheric gas would help us cool the planet, thus allowing life to settle.

There are several proposals, though many are technically challenging.

Paul Birch, for instance, envisions shading the planet, by using a huge space sunshade" (25,000,000 km^2), coupled with enormous vertical atmospheric pipes, to accelerate convection between the upper atmosphere and planetary surface.

Once cooled, carbon dioxide would liquefy under its own pressure, and resulting oceans should be covered by an artificial crust, over which an atmosphere, hydrosphere and biosphere would be built from scratch by importing materials from other regions of the Solar System [8].

It is a rational option, but the resource requirements to build the sunshade (although we might alternatively place swarms of smaller, light-reflecting satellites or asteroidal fragments in the Lagrange L1 point), to hide" the old atmosphere and create a new one are of unimaginable magnitude. Add the risk of permanently living with the equivalent of 9.3 MPa of lethal gas beneath your feet.

There are some other ideas, involving the mechanical removal of the atmosphere. We could trigger controlled impacts, with large-sized asteroids. The energy of each impact would eject some of the atmosphere into space. The problem here is that a large number of impacts are needed. At an average diameter of 16 km, assuming 100% efficiency, 2,000 such objects would be required. But, since efficiency cannot be anywhere near 100%, in the worst-case scenario, we would need two million asteroids to bring the atmosphere to 0.1 MPa [9, 10]!

A related version would involve some major impacts, with objects weighing around 10^{18} kg or more. Practically, about 200 Sycorax-sized objects are used the same way as on Mercury. The volcanism triggered would lead to carbon dioxide sequestration in lithospheric minerals [10].

Then, there is the option of atmospheric mining". We saw, in previous chapters, how a complex of orbital rings and mass drivers can be used to deliver CO_2 and N_2 to other celestial bodies. But we also saw the quantitative drawbacks (Subchapter **4.1**).

1,000 mass drivers, each launching a CO_2 mass equivalent to that of a small oil tanker per hour, would launch 2.5×10^{16} kg in a century. But the total mass of the Venusian atmosphere is 20,000 times larger!

So, while the physical removal of the excess atmosphere cannot be ruled out, it will surely not work alone.

Other ideas include atmosphere conversion through photosynthesis (inefficient and improbable since no known organism is able to perform photosynthesis in the upper atmosphere), using self-replicating devices (a technology that we still do not have) or limited colonization solutions, such as floating cities [9, 11, 12].

The most accessible solution seems to be that of chemically converting the atmosphere. And here, we have two options.

Carbon dioxide reacts to calcium and magnesium oxides, forming carbonates:

$$CaO + CO_2 \rightarrow CaCO_3$$

$$MgO + CO_2 \rightarrow MgCO_3$$

We obviously need a source of oxides. Mercury's lithosphere could be one, although importing 8×10^{20} kg calcium oxide, respectively 5×10^{20} kg magnesium oxide would pose some serious logistical problems.

The good news is that Venus also contains the two compounds, within its lithosphere and mantle. So, we could use local lithospheric deposits, but that still leaves us with a quantitative problem.

It is true that the planet's mantle seems to contain around 35.5-38% MgO and 3.2-3.6% CaO [13]. Unfortunately, some thermic particularities make the lava and, thus, the planetary crust, retain only somewhere below 10% MgO, a percentage lower than on Earth [14]. As a positive aspect, the lithosphere seems somewhat enriched in CaO, with up to 7% [15].

Yet, to excavate/blow up somewhere between 600 m and 1 km of Venusian crust would be a daunting task and would only help us solve part of the problem: it would lower atmospheric pressure to 4.3 MPa, while the planet would still be uninhabitable [9, 11, 16].

The only solution left would be to use asteroidal impacts strong enough to pierce the lithosphere, just as in Mercury's case (see the previous chapter). Objects hundreds of kilometers wide could expose the upper layers of the mantle, while inducing primary and antipodal volcanic phenomena, letting the MgO-rich magma and pulverized lithospheric particles do the job for as, by consuming excess atmospheric gas.

The main obstacle, in this case, is that we do not know how thick the crust of Venus is. Estimates are quite variate, from just 8-25 km [17], to 28-70 km [18], or even over 80-100 km [19]. In the first case, the situation would resemble that of Mercury and directed impacts would be effective. At over 50-80 km thickness, the difficulty of the entire process would increase dramatically.

However, the oxides of alkaline metals are not the only ones able to consume carbon dioxide; hydrogen is, too, through the Bosch reaction (see Subchapter **4.1**), generating carbon (graphite) and water.

We would need at least 4.15×10^{19} kg to accomplish the task [11]. Obviously, the mass ejected while helioforming Jupiter, around 10^{15} kg, would not be nearly enough.

The main possible source is giant planets, of course. A system like that mentioned above, involving networks of orbital rings and some 1,000 mass drivers per planet, with a capacity of 30,000 tons/hour, would supply about 25×10^{15} kg in a century. If we increase the ballistic capacity to 10,000 launchers per planet and consider all four gas giants (obviously, before helioformation), we would get some 10^{17} kg/century.

40,000 years would be necessary to finish the job. While the idea is not to be neglected, this is a very, very long time!

Now, let's see how efficient devices like that put forward by M. Culaj: toroidal structures having 20 km in diameter, designed to trap and concentrate solar wind (see Subchapter **4.3**)!

According to the original design, to be used on Mars, the planet would receive around 1,760 tons of hydrogen per hour [20]. Thus, over 15×10^{9} kg/year.

For Venus, the process could be optimized by adding mass drivers, to precisely target hydrogen pellets. At a similar distance to the L1 point, the incident mass would be of 13.8×10^{10} kg/year. The complete conversion of the atmosphere would require 300 million years, or just" 300,000 if we built 1,000 such devices (with a total mass of 5 million tons, a little more than the Palace of the Romanian Parliament).

Of course, in either case, we could, in theory, multiply the installations involved according to our needs. Yet, both orbital rings and solar wind accelerators are megastructures, whose construction and assemblage are in no way easy!

To the obvious costs, we should add those of seeding the atmosphere with ferric iron (Fe^{3+}) or nickel compounds as catalysts, to ensure the high efficiency of the Bosch reaction. Luckily, there are asteroids that have elevated amounts of both metals.

Basically, if we have enough available resources, we could end the whole process in a few centuries, by using hundreds of thousands of hydrogen mass drivers, hundreds of thousands of solar wind traps plus tens of major impacts, for lithospheric sequestration of CO_2 (Fig. **7.2**).

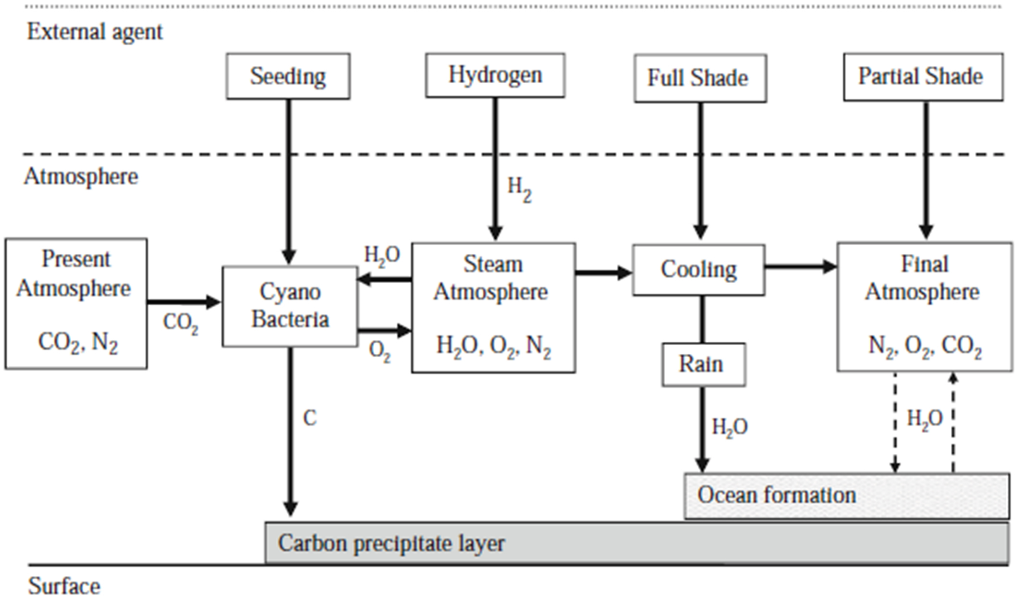

Fig. (7.2). A general schematic synthesizing various methods proposed for Venusian ecosynthesis [10].

Alternative proposals, like electrolysis of entire iceteroids or small icy moons orbiting gas giants, or fleets of automatized space tankers to ship the hydrogen to Venus are even less efficient [21].

Until now, for all the planets and moons discussed, I tried to select or imagine just those ensembles of terraforming methods that do not involve technologies that are yet undiscovered, unavailable, or megastructures that are too difficult to build.

But now it’s the moment to introduce a concept that, for the moment, seems rather specific to science-fiction literature and filmography than to current technology. And there is an excuse for that: besides terraforming Venus, that technology is vital for the future of humankind in the Solar System and, especially, beyond. So, we should start researching and achieving some progress in this field, as soon as possible.

7.2. BABEL

Go to, let us build us a city and a tower, whose top may reach unto heaven; and let us make us a name, lest we be scattered abroad upon the face of the whole earth!" (Genesis, 11:4). You are probably familiar with the story of the Tower of Babel, through which, apparently, the builders wanted to get closer to God.

And most people imagine it as an extraordinarily tall building, which is somewhat illogical since any mountain would surpass its height.

Few think of its etymology: *Bab-El* simply means The Gate of God" (although the actual location is not specified, tradition places it in the city of Babylon, *Bab-Ilani*: The Gate of Gods"). So, maybe Biblical characters involved in this story were smarter than they might seem, after all.

What are we talking about? Physicists call them to *distance contractions*, *Einstein-Rosen bridges* or, simpler, *wormholes*.

The concept was first introduced in 1916, by Ludwig Flamm, as a consequence of the Theory of General Relativity. In 1935, Albert Einstein and Nathan Rosen took a step further, postulating the existence of some bridges" that connect different regions of the space-time continuum.

Such a bridge would allow matter and energy to transfer at any distance. While an object would travel through it at normal speed, if the distance is long enough, the overall velocity observed from the outer Universe would surpass the speed of light (Fig. **7.3**) [22].

The existence of such bridges raises several problems. First, in the initial model, the wormhole resulted from connecting a black hole (a type of object with an extreme density that we now acknowledge) and a so-called *white hole*, a structure of the extremely concentrated negative mass.

Black holes are now rather familiar. We know they are formed, for instance, when a massive star collapses, at the end of its life cycle. And theory says that there are also other ways such an object can appear. However, nobody has ever seen a white hole. Things get even weirder when we consider what such a hole should be made of.

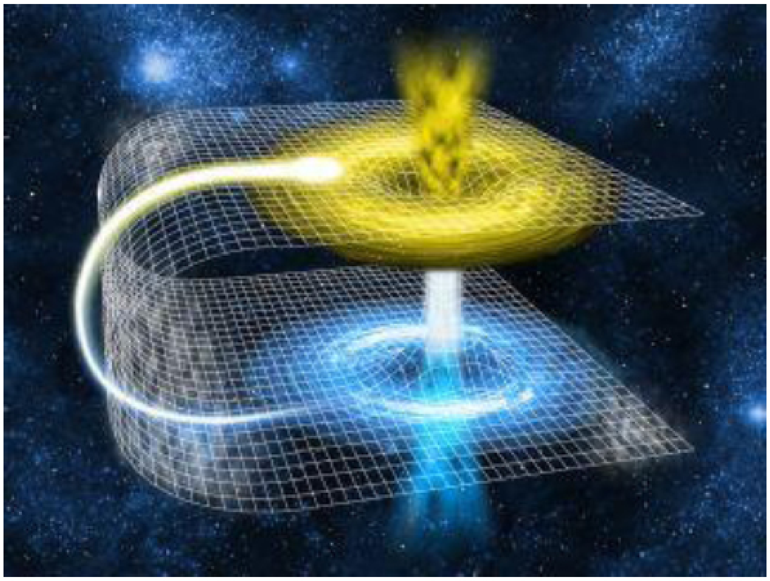

Fig. (7.3). The general schematic of a wormhole": a spacetime tunnel allowing transport over great distances, bypassing" regular space [22].

For a wormhole to function and the spacetime tunnel to remain open at both endings (*i.e.*, to have that mysterious white hole in place), some amount of exotic matter is necessary.

Unfortunately, when physicists mention exotic matter" they do not mean coconuts. In this case, we are talking about a negative matter. Just like antimatter (that is also something we know exists, and we can even produce it, in tiny amounts) is the electromagnetic opposite of usual matter (with negatively-charged atomic nuclei, orbited by positive particles), the negative matter is the gravitational opposite of normal matter, having actual antigravitational properties: the more there is gathered in one place, the more it tends to repel itself!

Obviously, negative matter has never been observed. It would be difficult, since negative gravity itself makes it impossible to agglutinate.

Second, according to initial predictions, naturally-occuring wormholes – most formed during the first stages of the Universe – would only have extremely small sizes (about 10^{-33} cm). Add low stability, which makes them quickly collapse at the tiniest amount of energy that passes through them, as long as they lack sufficient amounts of negative matter. Finally, it is rather difficult to predict where such bridges lead to [22].

Lately, wormhole theory has made some progress. Thus, we know that extreme gravity should trigger their formation, so we can look for their ends around black holes [23]. Also, new models show that maintaining a wormhole open might only require very small amounts of negative matter [24].

In the meanwhile, other theoretical advances seem to completely rule out the need for white holes and negative matter.

For instance, there is a theoretical possibility that the so-called quantum entanglement can join two black holes, a phenomenon that makes two particles or particle ensembles behave identically, no matter the distance between them. While possible, naturally-occuring quantum entanglement of two black holes is extremely unlikely, due to the necessary precision [25].

Taking a step further, the issue with black hole is that they expel matter and energy from this Universe. Part of the energy is released back as electromagnetic radiation, which progressively causes the black hole to evaporate.

So, where does the rest of the information go?

A group of researchers from the California Institute of Technology, led by dr. Sepehr Nezami, seems to have discovered the missing link: through quantum entanglement, two black holes can reciprocally exchange information. Briefly, whatever falls into one of them will be expelled from the other [26]!

And another step further... How do two black holes get entangled?

It seems that the phenomenon is connected to their electric charge. According to another team of researchers, some black holes can get an electric charge during their formation. While theoretically possible, calculations show that such objects rarely occur in nature and have a rather low electric charge: a higher one would prevent an efficient gravitational compression.

Even according to this model, the resulting wormhole (Fig. **7.4**) seems to be unstable, while the attraction between the two black holes might lead to their collision, thus destroying the bridge.

For the second issue, authors suggest using cosmic strings, some yet hypothetical topological defects” in the structure of the Universe. They also put forward a recipe” to create wormholes, which unfortunately remains purely theoretical [27].

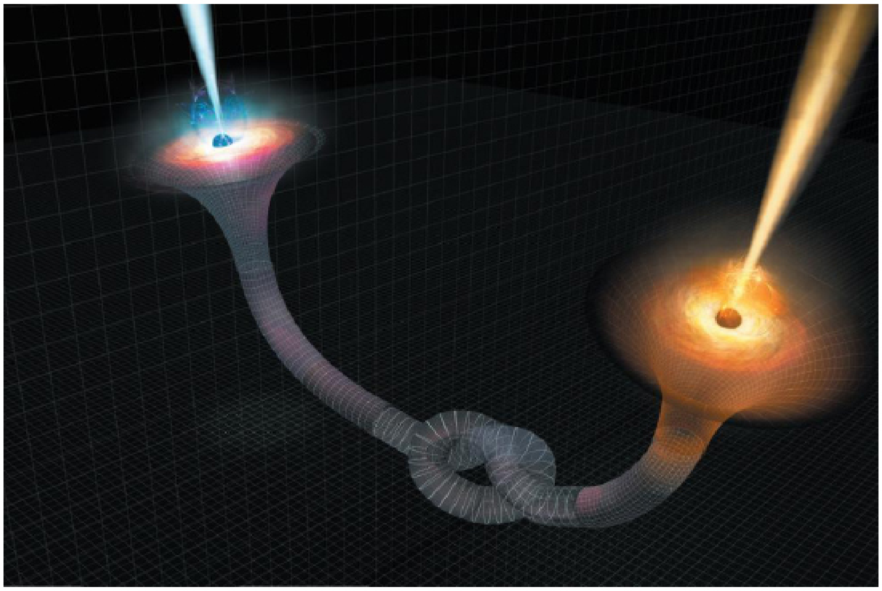

Fig. (7.4). Wormholes could be produced by connecting together two black holes, through quantum entanglement [33].

Yet, there might be another possibility! Black holes are not necessarily those massive objects created after large-sized stars collapse. As we already saw (Subchapter **5.1**), there should also be some ultramicroscopic ones, that remain from the beginning of the Universe, or ones that are constantly created by high-energy particle collisions (in particle accelerators in the upper atmosphere).

Nezami's team already considers creating some subatomic wormholes in the laboratory, in order to use them in quantum circuits [26].

The problem with micro black holes is their ridiculously short lifespan, ending with evaporation in a fraction of a second. Those occurring in particle accelerators also have the drawback of starting with an initial speed so high that, even if they survived long enough, they would be quickly expelled outside Earth's orbit [28].

We know that black holes can fuse together, when they get close enough to reciprocally attract. This phenomenon occurs in nature and results in a bigger black hole, having a mass slightly lower than the sum of the colliding holes' masses [29].

Thus, the main technical obstacle at the moment is the capacity to compress fast enough any number of micro black holes (naturally or artificially created), in order to obtain a larger-sized one. Then the stabilization of the resulting hole should follow, probably by giving it an electric charge and controlling it by using electromagnetic fields [30].

But, if we manage to get past this obstacle, could we create traversable spacetime bridges? First of all, some novel mathematic models show that, once produced, a traversable wormhole stays open and stable, indefinitely. Thus, there is no risk of not getting to our destination because the wormhole suddenly collapsed [31]!

Also, when working with wormholes, there is always the concern that the matter transported could be crashed, ripped apart or somehow altered by gravitational forces. Well, researchers calculated that a high transit speed would lower the impact of these forces within reasonable limits. There is an analogy with passing your hand over a flame: if the velocity is high enough, you won't get burned!

So, in theory, even complex objects like the human organism or a spacecraft could travel through wormholes and stellar black holes [32].

Dr. Daniel Jafferis, together with a team of physicists from the Harvard and Stanford universities, have proven, again through mathematical modelling, that wormholes can be traversable and stable, even at sizes that would allow a human being to pass through. It is just that, according to this model, these bridges are quite twisted", and travelling through them would take more time than covering the same distance through normal space [33, 34].

Finally, one of the top experts in this field, Dr. Mohammad Mansouryar, managed to model a traversable wormhole (meaning traversable for human beings) that is stable and controllable, without requiring exotic matter, conventional black holes or cosmic strings.

Briefly, instead of a continuous tunnel connecting two black holes, he proposes an array of asymmetrical cavities, whose asymmetry allows complying with the null energy condition, without any need to actually produce negative energy.

Propulsion through such a wormhole would be ensured by magnetic fields, while steering would be achieved by nonlinear control. We are talking, of course, of a model that is still purely theoretical, in the course of being tested in the laboratory, at an extremely small scale [35].

No matter what Einstein-Rosen bridges will be produced, such transportation means are essential for the future of humankind, since they can ensure human and cargo transfer in a reasonable time, even on the enormous interstellar distances.

But you will surely ask what they have to do with terraforming and colonizing Venus. Do not worry, for now, and we are not sending anybody there through a wormhole! However, we can send huge amounts of hydrogen, in order to convert the local atmosphere.

Let's take Uranus, for instance, one of the giant planets still not helioformed! Its atmosphere contains over 82% hydrogen and 15% helium (of the planet's volume, if we consider the mass, helium reaches about 26%).

In the low Uranian troposphere (some 300 km inside the atmosphere), temperatures reach 47°C, while pressure is around 20 MPa [36, 37]. A pressure that can be easily withstood by and human-made structure.

And now, let's assume we install one of the ends of an artificial wormhole at that point, the other end is located on the surface of Venus. Not a big hole, but one just 1 m wide.

A quick calculation shows that the flow rate through this hole would be 7,114 kg/s! Thus, 2×10^{11} kg/year. A 10 m wormhole would transport 2×10^{13} kg/year. 100 holes having 10 m each would ship no less than 2×10^{15} kg/year.

But, what happens if we increase the pressure? If we choose not Uranus, but Jupiter or Saturn (obviously, prior to helioformation) and we take the end of the wormhole down to an area with a 1 Gpa pressure (see Subchapter **5.1**), through a 10 m wide bridge, 1×10^{14} kg could transit yearly. Thus, 100 such structures would ship the entire amount of hydrogen needed in 4,000 years, while 1,000 wormholes would do it in four centuries [38].

It is not exactly quick, but surely more efficient than any other method. Wormholes would practically work as some oversized cosmic taps!

Hydrogen would start flowing and reacting to local carbon dioxide. Helium, a light gas, would lift towards the upper layers of the atmosphere and gradually get lost to space. Methane, a gas also found, in small concentrations, in the atmospheres of gas planets, should be oxidized once an oxygenic atmosphere is produced through photosynthesis.

7.3. PARADISE

Unfortunately, converting or removing the excess atmosphere does not end all our problems.

Although it might seem counterintuitive, the process would further warm the planet. Keep in mind that water vapor has an even stronger greenhouse effect than CO_2, while the Bosch reaction is exothermic. Add the small amounts of methane imported, along with the hydrogen, from the gas giants.

A temperature above 296°C, even at the high pressure on Venus, prevents water from condensing [11]. Thus, chemically converting the atmosphere does not spare us from finding a way to cool the planet.

One of the most subtle solutions addresses the chemistry of the upper atmosphere. Venus possesses thick, opaque clouds made of water vapor and sulfuric acid, that reflect some 75% of the incident thermal energy. As we saw in Mercury's case (see Subchapter **6.2**), this detail can be used in regulating global atmospheric temperatures.

Controlled impacts with asteroids or small moons diverted from their orbits around gas planets (having tens of kilometers in diameter) would pierce through the lithosphere, especially if it proves to be rather thin (8-22 km), an aspect also discussed in a previous subchapter.

Besides chemically sequestering some of the CO_2 as carbonates, the volcanism triggered this way would also result in releasing new amounts of SO_2. By chemical photodissociation and reaction with water vapor, it would increase the thickness of high-altitude clouds, thus increasing atmospheric albedo.

As we saw, the anti-greenhouse effect can get to extreme values on some celestial bodies – up to 90% on Titan.

This does not mean that there are no other available solutions, to be used in parallel with chemical ones.

We already discussed ways to shade the atmosphere, and we saw that a sunshade placed in the Lagrange L1 point would be effective but unimaginably expensive.

Yet, there are alternatives. If we combine several cooling means, including SO^2, the sunshade would not necessarily need to be continuous. And we might not even need swarms of minisatellites.

Asteroidal debris should be enough. So, we should bring a massive asteroid, formed of ice and other soft" materials, into a stable orbit around the Sun, at a point located beyond L1 and blow it up through thermonuclear explosions, creating a cloud of dust, rock and ice fragments. These would not shade the planet entirely but still reflect part of the incident sunlight.

Another option is to dismantle an asteroid directly into the Venusian orbit, generating a ring of debris disposed obliquely to the planet's equator. Anyway, creating a ring of solid fragments will be needed in order to build the Dyson spin motor (see Subchapter **5.3**), so why not giving it a double use?

The ring made up of dust and rocks would permanently shade vast areas of the Southern Hemisphere (Fig. **7.5**). Again, not entirely. But lowering insolation in the southern regions of Venus, coupled with the long day, during which a longitudinal hemisphere stays in the dark for tens of terrestrial days, the dust cloud at the L1 point and the sulfuric acid clouds, would lead to a major decrease in average incident sunlight and an effective cooling [11].

Another solution is that of heat pipes: artificial structures, 50 km tall, through which a working fluid (optimally, a mixture of water and ammonia) is continuously recirculated. The fluid condenses at the upper end of the pipe and flows down to the base, where, in contact with the hot atmosphere, it turns to vapor and goes up again.

According to the estimates of P. Birch, a total fluid volume of 2.5×10^{13} kg would be required, while the cumulative volume of all heat pipes should reach 2.5×10^{13} m^3 [8]. At the height of 50 km and a diameter of, let's say, 200 m, some 16,000 pipes would be needed to accelerate atmospheric cooling 1,000 times. Much less if we use them in combination with other cooling techniques.

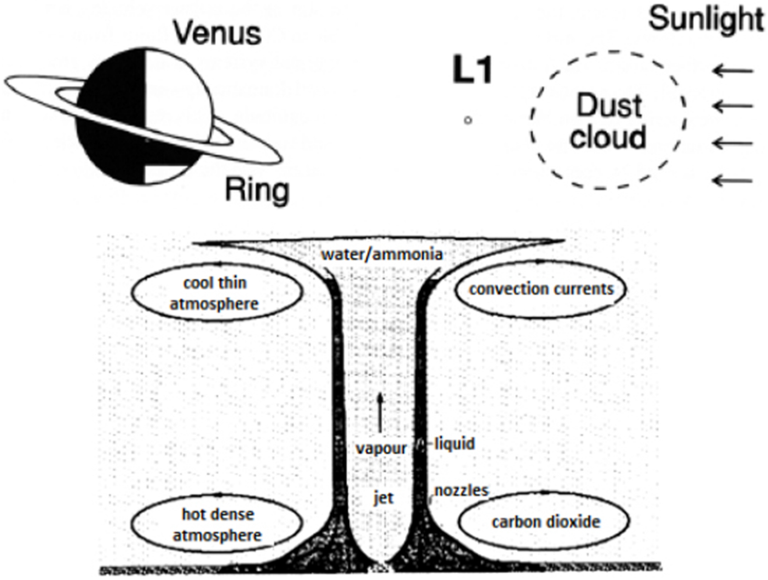

Fig. (7.5). Technical methods proposed for cooling the Venusian atmosphere: orbital shading with asteroidal debris [11] and heat pipes" [8].

And, even if they sound like SF megastructures, such heat pipes can be easily and conveniently built by using the SpaceShaft technology (see Subchapter **3.1**): inflatable" structures extruded from their bases.

Gradually, as atmospheric temperatures drop below the limit of 296°C, water starts condensing. Years after years of rains would create an incipient hydrosphere that would also help sequester some of the CO_2 as carbonate minerals.

In the meantime, atmosphere conversion would continue until just about 20 kPa of CO_2 would be left. Or even less, since part of the water vapor would dissociate photochemically, already generating some amounts of oxygen. Water pouring continuously from the sky would create a vast planetary ocean, equivalent to an average water layer 880 m thick. This means less water than on Earth, but the flat landscape means it would cover 80% of the planet's surface with oceans, seas and lakes, with an average depth of around 1,000 m.

Furthermore, a graphite layer with an average thickness of 100 m would cover the ground. The whole process would last for somewhere between 300-1,000 years [10, 11, 16].

We saw that it is not difficult to create an artificial magnetosphere, in order to protect the planet from noxious radiation and prevent the atmosphere from being eroded. And a Dyson spin motor would give it a much more pleasant rotation rate, of just 8 days in 280 years, while in around 2,220 years, a day on Venus would get as long as one on Earth.

Cumulated, the whole Venusian ecosynthesis should last, under optimum conditions, about 700 years. This does not mean that, once liquid water appears and temperatures drop below 74°C, we cannot start introducing the first life forms.

Just as in Mercury's case, we are talking about photoautotrophic, thermophilic and acidophilic micro-organisms, such as *Synechococcus*, *Cyanidium* and especially *Mastigocladus* and *Chlorogloepsis*. And I say especially", because nitrogen fixation would be a crucial process.

The atmosphere of Venus contains over 300 kPa of molecular nitrogen. This means that, even after we end the conversion and close the wormholes, there would be a total atmospheric pressure three times higher than the terrestrial one. Tolerable by human beings (see Table **4.1**), but not really pleasant. Thus, lowering nitrogen pressure to more earthlike" values is a priority.

In the meantime, living conditions would progressively improve, the atmosphere would become richer and richer in oxygen, and temperatures would become similar to those on Earth. Oceans would decrease their acidity, and the sulfuric acid clouds would disappear, after a period of acid rains and reactions with crustal minerals, forming sulfates [9].

One of the main ecological problems left would be graphite. Obviously, it would not remain as a continuous layer, being washed away by rains and blown away by winds towards oceanic basins and other depressions of the crust.

Graphite is not really friendly" to microbial life. Although it is, practically, pure carbon, thus one of the key elements of life, it does not provide any other valuable nutrient. Even more, the spiny" surface of this material tends to deteriorate cell membranes. On Earth, researchers are trying to use it for producing antiseptic plastic materials, because it can kill around 99.99% of the bacteria that dare to colonize it [39].

And yet, this does not mean that graphite is entirely inert from a biological point of view. First, it tends to get weathered by oxidation, for instance, when it comes in contact with sulfuric acid, affecting its structural integrity. Second, there are many bacteria that, by electrostatic mechanisms or abundant exopolysaccharide secretion, are still able to attach to its rugged surface, avoiding cellular damage [40].

Furthermore, numerous bacteria possess the enzymatic mechanisms needed to biodegrade graphite. We can mention *Acidithiobacillus ferrooxidans*, *Burkholderia kururiensis*, *Delftia acidovorans*, *Stenotrophomonas maltophilia* or *Trabusiella guamensis*. These are the micro-organisms that normally degrade, in a natural manner, graphite waste and derived materials (graphene, carbon nanotubes *etc*.) that are produced in larger and larger amounts by our industry. They do so by adapting metabolic pathways that are normally involved in decomposing naphthalene, other polycyclic aromatic hydrocarbons or lignin.

We can also add some fungal species, like *Trametes versicolor*, *Sparassis latifolia* and *Phanerochaete chrysosporium* [41, 42].

So, graphite could be metabolized or slowly covered by soil, on landmasses, respectively by sediments, in water basins. Gradually, in areas where this material is removed, we should introduce thermophilic cyanobacteria and then lichens (*Peltigera scabrosa*, *P. rufescens*, *Biatora granulosa*), the moss *Campylopus pyriformis* or land plants such as *Lycopodiella cernua* and *Kunzea ericoides*, just like on Mercury.

And also, like in Mercury's case, tropical peatlands, with species of sedges, such as *Cladium jamaicense*, would play a key role in accelerating carbon dioxide removal from the atmosphere (Fig. **7.6**).

However, unlike other planets, Venus has all the resources needed to create a luxuriant biosphere: carbon, nitrogen and microelements at our disposal. With a gravitational acceleration similar to the terrestrial one, a breathable atmosphere and an extensive hydrosphere, close to the Sun but now protected by an artificial magnetosphere, Venus would be more than pleased to human colonists.

Fig. (7.6). *Cladium jamaicense*: a peat-producing sedge species and important plant in terraforming hot planets [43].

For a long time, people thought that the planet's dense atmosphere and opaque clouds enclosed a paradisiacal world, warm and wet, covered by endless rainforests. And, up to 700 million years ago, Venus really was a warm, wet and hospitable world. Now, in a few millennia (maybe even less than 2,000 years), thanks to the sustained effort and ingenious use of technology, *Homo sapiens* could return to that status.

Venus has a surface with relatively low altitude gradients compared to other planets. Yet, there are two major "landmasses", going up to plateaus up to 3-4,000 m above the base level. The largest is Aphrodite Terra, the size of Africa, located in the Southern Hemisphere, close to the Equator. Ishtar Terra is located in the temperate-cold" area of the planet, between 60-75°N. Besides them, there are other, smaller, future continental masses or islands (Fig. **7.7**) [11].

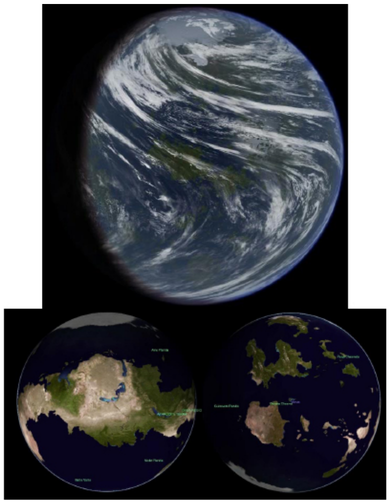

Fig. (7.7). Artistic vision of a terraformed Venus [16] and the distribution of future landmasses [44].

Although it will take some time, on the vast tropical continent, we could even recreate, species after species, ecosystems such as terrestrial rainforests. Other areas would be allocated to agriculture and human habitation [43, 44].

The shallow oceans would be full of life; after introducing various species of coral, we would have reefs and atolls. People from all over the Solar System will come here to admire the fine, white sandy beaches and relax under the coconut trees.

A true tropical paradise awaits us as a reward for taming this hostile world!

CONCLUSION

Terraforming Venus is much more difficult than any other similar process seen so far. Due to the extreme local conditions, it demands novel technologies, lots of resources and time.

Again, the most suitable approach should be synergistic, involving atmospheric conversion and gas sequestration. While simple" mega-scale engineering could accomplish the task, in order to achieve results in a reasonable time, we would need wormhole technology, or some equivalent, in order to ship large amounts of hydrogen from gas giants. Even so, the process could take many centuries, if not millennia.

The second stage would be cooling the planet, by several planetary engineering means, thus allowing the introduction of photosynthesizing life forms.

But, if we succeed, humanity would get one of the most pleasant new homeworlds possible. A (mostly) warm paradise, with living conditions as close to the terrestrial ones we can get in this star system.

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CHAPTER 8

The Edges of the System

Never say "it's impossible", but start with, "let's see."
Nicolae Iorga

Abstract:

The Outer Solar System is an enormous region, offering plenty of potential living space and valuable resources for humankind. It comprises Uranus and Neptune with their moon systems, myriads of trans-Neptunian dwarf planets and planetoids including Pluto, Charon, Eris *etc.* and putative planetary or substellar-sized objects.

The most feasible approach for ice giant planets seems to be helioformation, followed by terraforming and colonizing their moons, using methods similar to those that should be employed on Jupiter and Saturn.

Since many other celestial bodies are too far from any light source, turning them into habitable worlds requires altering their orbit. While such a process requires a carefully-planned and sustained effort, it would be made easier by the low mass of these planetoids.

Keywords: Changing orbits, Helioformation, Moons, Nemesis, Neptune, Terraformation, Trans-Neptunian objects, Tyche, Uranus.

Until now, we have studied nine main terraformable and habitable worlds (besides Earth, of course). And at least the same number of secondary terraformable or paraterraformable bodies, plus the plethora of asteroids and small-sized moons suitable for paraterraformation, hosting underground habitats, or O'Neill colonies.

Ten worlds are open to human colonization. At a quite reasonable average of five billion inhabitants for the main planets and secondary ones (like Ceres, Rhea *etc.*), we get a total population of 100 billion people! And, with a bit of effort, we can even increase this number.

Does this mean that we should stop here? Definitely not! The Universe does not just mean the Inner Solar System. At more than 19 astronomical units from the Sun, towards the cold and dark edges of the System, new worlds await us,

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offering new resources and new promises. There are the two giants made up of gas and ice, Uranus and Neptune, with lots of moons, larger or smaller. Then, there is a multitude of dwarf planets, including Pluto and Charon, Eris, Sedna or Haumea. Plus, countless tiny and icy objects form the Kuiper Belt and Oort Cloud. And there might be something bigger and more spectacular lurking in the shadows.

Beyond these edges, there is the infinite Universe! So, come along with me on a journey toward new, strange and wonderful realms!

8.1. A KEY DECISION

Besides Jupiter and Saturn, our star system possesses two other giant planets. Once considered *gas giants* and, nowadays, *ice giants*, Uranus and Neptune are two "twin" planets with extremely similar sizes and structures (Fig. **8.1**).

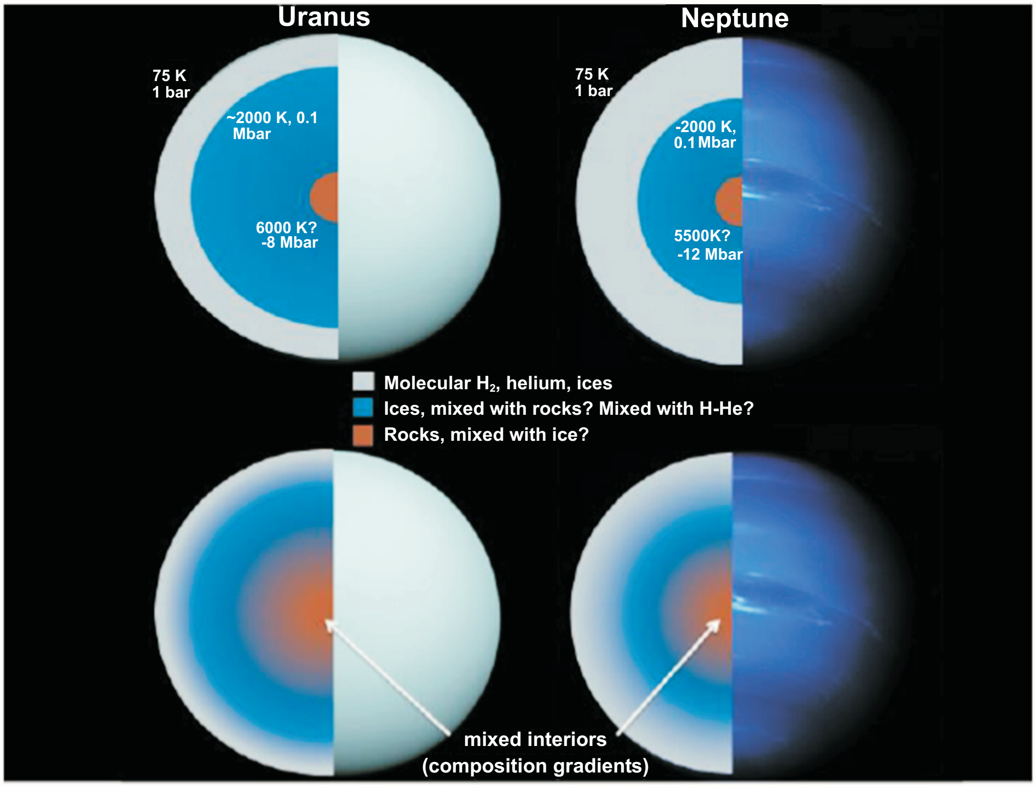


Fig. (8.1). The internal structure of Uranus and Neptune: the layered version and that of density gradients [1].

Located at 19, 30 astronomical units from the Sun, having masses 14.5, 17 times larger than Earth's and colored in different tones of blue, the two enormous planets are somehow different from their larger "neighbors" in terms of mass and composition.

Outside is an atmosphere made of hydrogen (over 70% of its mass) and helium, with an unknown depth. This is because there are several concurrent models of the possible internal structure: atmosphere, "mantle" made of ice and a rocky and metallic core, all of them clearly separate; undemarcated atmosphere and mantle, with separate core; separate atmosphere with undemarcated mantle and core; finally, a continuous density gradient, from the gaseous atmosphere to the solid core, without any clear boundaries (Fig. **8.1**).

Thus, we may either have an atmosphere hundreds of kilometers thick (around 300 km, on Uranus), followed by thick layers of ice (where "ice" is the term used by astronomers for layers dominated by water, methane, ammonia *etc.*, no matter what their state of matter is), or a continuous atmosphere, extending, as far as 80-85% of the planets' radii [1, 2].

And here we have uncertainty and a decision that our descendants will have to make at one point. Are Uranus and Neptune helioformable? So, can we transform them into mini-stars and terraform/colonize their moons? If so, is this the optimal choice, or can we use the two giants in another way?

To start with, the amount of hydrogen in each of them equals just twice Earth's mass. Of course, this means an impressive amount, but compare it to the hydrogen equivalent of 300 Earth's masses, in the Jovian atmosphere [2]!

But the fuel required by nuclear fusion does not necessarily need to be molecular hydrogen! Water and methane can work as well, especially where there is a high enough concentration of deuterium or tritium (^{2}H or ^{3}H). A ratio between deuterium and protium of 1:300 seems to be enough to help propagate an explosive chain reaction [3].

Furthermore, there are current proposals to use methane pellets as a fuel for future fusion power plants [4], including a form called *methane diamond* (crystallized methane) [5], a type of material that seems to naturally occur in the deeper layers of both planets.

As for the ratio of deuterium and protium, it is even higher on Uranus and Neptune than on the other giant planets (where, again, it is anywhere between 10^{-4}-10^{-5}), but lower than in cometary nuclei and even Earth's oceans [6, 7].

Some models of the internal structures of ice giants show a probable concentration of deuterium in ice grains located close to the core [7]. Furthermore, Ouyed and collaborators extrapolated their model of a compact, deuterium-enriched layer (with a ratio of 10^{-3}; see Subchapter **5.1**) to all giant planets, including Uranus and Neptune, with some degree of uncertainty regarding its shape and location. According to the authors, there can be natural deuterium fusion processes that would explain the amount of thermal energy radiated by such celestial bodies [8].

However, if we take into account the heat radiated into space, there could be a difference between the two planets. Neptune, just like Jupiter or Saturn, emits more than twice the amount of heat received from the Sun. But Uranus does not [9].

Several proposed mechanisms could explain this heat generation, but if the model mentioned above is correct, Uranus might not have the same concentration of deuterium or, for various reasons, internal fusion reactions are less intense.

Obviously, in the case of a chain reaction, the planetary mass is too large to allow an explosion. Thus, once perpetuated by deuterium-rich layers, it would spread through the whole planet, making Uranus and Neptun the fourth, respectively, the fifth star of the Solar System!

Is this possible? Is it feasible? Although there are arguments against it, nobody can stop us from trying! Thermonuclear warheads are among the few things that superabound on Earth!

What would be the effects? Jupiter is about 20 times more massive than any of the two planets, while Saturn is 6 times bigger (5.6 times heavier than Neptune and 6.5 times heavier than Uranus, to be precise). Thus, the amount of nuclear fuel inside the ice giants is significantly lower.

Also, the percentage of hydrogen is surely lower, too. Yet, there are other isotopes that could be "caught" in fusion reactions, like ^{17}O și ^{18}O (on Earth, at least, the proportion of ^{18}O surpasses that of deuterium, at a ratio that is probably similar on other worlds in the System) [3].

As we saw in Chapter 5, it is difficult to model the results of helioformation, for the simple reason that nobody ever did such a thing, nor do we know any natural or artificially helioformed gas giant. We are, again, on shaky ground.

In Jupiter and Saturn's case, we estimated a final luminosity around 10^{-4}-10^{-5} of the solar one. Thus, for Uranus and Neptune, we can probably assume a ratio of

10^{-5}-10^{-6}. Also, it is difficult to estimate what the lifespan of these new stars would be. Small stars tend to live long, but they also tend to be very dim.

On the other hand, artificially-helioformed planets, having luminosities above those in the luminosity/mass curve of main sequence stars, could compensate by shorter lifespans. In the worst-case scenario, Jupiter or Saturn could light the sky for millions of years. But that means that the lifespan of a helioformed Uranus should be of just several hundred thousand years.

For the moment, it is hard to say. So, we need to know which of the two planets is worth turning into a star. Let's check their main moons (Table **8.1**)!

Table 8.1. Some of the largest moons of Uranus and Neptune [10].

Planet	Moon	Radius (×Earth Radii)	Distance From Planet (×Millions km)	Gravitational Acceleration (g)
Uranus	**Titania**	**0.135**	**0.436**	**0.038**
	Oberon	**0.119**	**0.583**	**0.034**
	Ariel	**0.091**	**0.191**	**0.027**
	Umbriel	**0.092**	**0.266**	**0.023**
	Miranda	0.037	0.129	0.008
Neptune	**Triton**	**0.212**	**0.354**	**0.079**
	Proteus	0.033	0.117	0.007
	Nereid	0.027	5.514	0.007

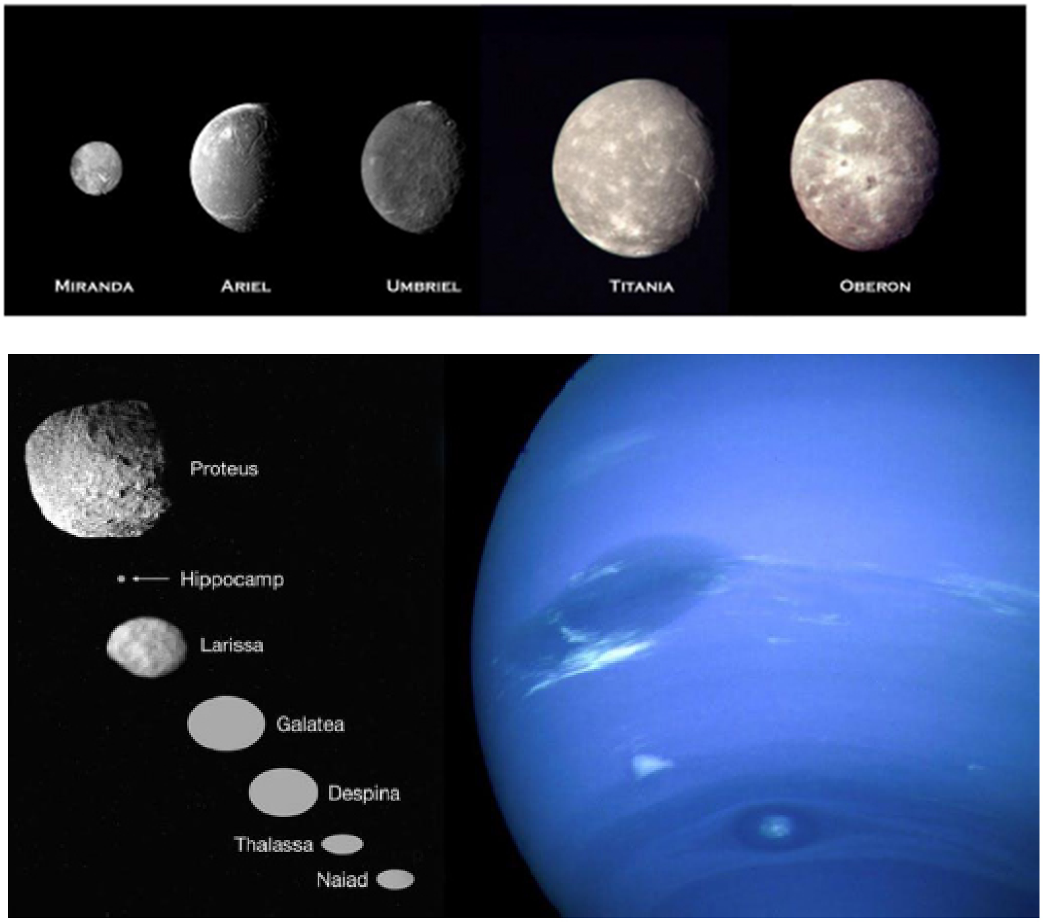
All those are followed by a plethora of objects with diameters below 200 km, such as Sycorax and Caliban, mentioned in Chapter 6. Tens of small moons, having beautiful names like Belinda, Larissa or Despina, moons that are suitable for building O'Neill habitats or for using them as sources of water and volatiles for other terraformation projects in the System, or just as projectiles meant to pierce planetary crusts (see Chapters 6 and 7).

In this table, objects written in bold have a gravitational acceleration higher than 0.01 g. Except for Triton, we are talking about actual dwarf planets, similar to Ceres and the secondary moons of Saturn (Table **5.1**). The noteworthy exception is Triton, somewhat more similar to the major moons of Jupiter and Saturn and having a gravitational acceleration equivalent to half of the Moon's.

We already saw that such bodies could host more than just underground habitats: they can be fully terraformed, although, for the smaller ones, paraterraforming is more advisable. Thus, beneath a "roof" made of aerogel, they could keep their atmospheres long-term (meaning more than a few million years; we shall see how long the fuel inside the new stars will last).

For all these large moons, the distance to the giant planet they orbit is much shorter than 1 million km, which is very good. We saw that one-hundredth of an astronomical unit would probably be the optimal distance from a helioformed Jupiter. For Uranus and Neptune, a shorter distance would compensate for the lower luminosity.

The "jewel in the crown" is, of course, Triton. A bizarre, cold world, similar to Jovian moons or Pluto. It is assumed to have originated as a Kuiper Belt object, trapped by Neptune's gravity (Fig. **8.2**).



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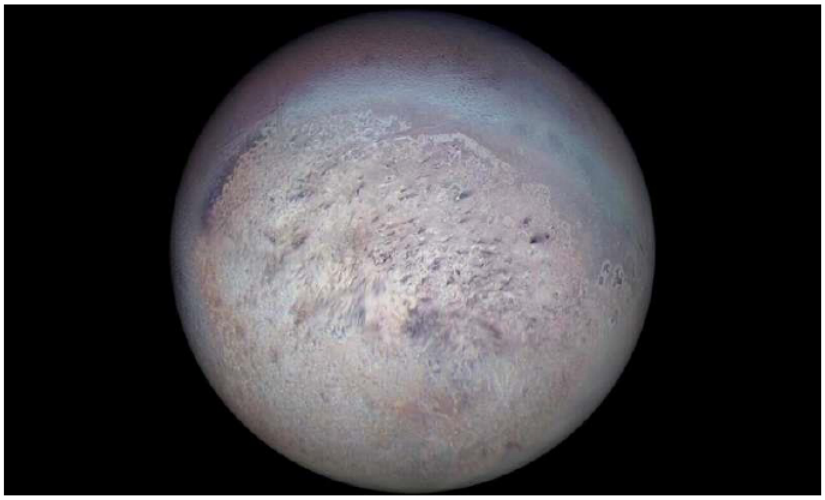

Fig. (8.2). Some of the main moons of Uranus [11] and Neptune [12]; Triton [13].

It is covered by a crust made of frozen nitrogen (55%), carbon dioxide (15-35%), carbon monoxide and ammonia. Beneath this is a mantle formed of multiple types of ice, probably with liquid or semiliquid layers and a core made of rock and metals. It has forms of cryovolcanism, with regular eruptions of ammonia, water and other light compounds [10 - 12].

Although conventional models show, just like in the case of other icy moons, a degree of stratification between icy and rocky regions, the high percentage of rocks (75%) and its origin in the coldest areas of the Solar System suggest a fast cooling following its formation, thus generating a rather homogenous inner structure, similar to that of Callisto or Ganymede [13 - 15].

The same situation seems to be true for the largest Uranian satellites. Except for Miranda, all the other moons have a higher density than Saturnian ones, suggesting a higher percentage of rocky material and the lack of strict layering [16].

We discussed, in Subchapter **5.2**, how important is this weak differentiation of constituent layers: it prevents a moon, once adequately warmed, from becoming a "waterworld”. We are talking about five major moons with significant reserves of life-supporting elements (water, nitrogen, carbon. *etc.*), with future landmasses located conveniently from the new stars.

Triton could be integrally terraformed, hosting luxuriant ecosystems and billions of people on its surface (Fig. **8.3**). Titania, Oberon, Ariel and Umbriel could also support integral terraformation, although it should be noted that, in order to maintain the atmosphere and habitability over a longer period of time, aerogel membranes would be required. Maybe not from the beginning, but the loss of gases will be significant after several hundreds of thousands/millions of years.

Miranda, Proteus *etc*., are meant for complete paraterraforming and/or creating underground habitats. Smaller satellites, having kilometers or tens of kilometers in diameter, are only suitable for either partial paraterraforming and underground settlements or O'Neill colonies.

But why did I mention a choice in regard to the two ice giants? Because there is an alternative idea, circulating around the online media: terraforming Uranus, respectively Neptune. And, although it would be a titanic endeavor, let's take it into account!

It is possible that helioforming may not work. It is also possible that our descendants prefer increasing the lifespan of one of the helioformed planets, giving up the other and using it as a fuel source.

If you had to choose, what would you do? Neptune has one main moon, Uranus has four, and their combined surface areas are almost equal. And Triton would be much more pleasant to inhabit than the small Uranian moons. On the other hand, helioforming Neptune seems more likely to succeed, while an eventual terraformation of Uranus (already tricky, as you will see) is made even more difficult by its perpendicular rotation.

Might terraformation be an option when the nuclear fuel ends? We have no idea, since we do not know how a helioformed planet will behave at the end of its nuclear activity cycle. But, even if it cooled down, becoming a planet again, it is difficult to imagine its new structure. This is why the decision should be made right from the beginning.

Although massive and gaseous, both planets possess cores of rock and metal, probably similar in structure to telluric planets. We do not know exactly how large these cores are, with estimates varying between 0.5 and 3.7 Earth masses (compared to an ice amount of 9-13.5 Earth masses!). Most researchers think that cores are about as heavy as our planet [2].

Recent models involve Uranus, a core having 55% of Earth's mass and 80% of Earth's radius [17]. Thus, if we remove the core from the rest of the planet, we would have an object with a gravitational acceleration of around 0.86 g at ground level.

Neptune's core seems denser, with 1.2 Earth masses at the same radius, thus a gravitational acceleration of around 1.88 g [18].

As you already guessed, the theory sounds like this: the atmospheres and icy layers of the two planets (or only one of them, at our choice) would be stripped away, until only the core remains, plus an adequate amount of volatile, life-supporting compounds. This would result in creating telluric planets similar to Earth, which, once heated enough, would turn their volatile reserves into atmospheres.

The ice stripped away could even be used to create new habitable moons or dwarf planets (practically, new "sisters" for Triton, Titania *etc.*), while the hydrogen could be directed to other terraforming purposes or, if, we terraform only one of the two giants and helioform the other, to fuel the latter and increase its lifespan. And, of course, we should give Uranus a decent sense of rotation [19, 20].

A scientific study shows that some smaller gas planets, of Neptunian type, could naturally turn into telluric planets by losing vast amounts of gas. This occurs when their orbits are altered, and they move closer to their stars. Not very close, but right in the Goldilocks zone, at an incident radiation level similar to that on Earth.

This way, *habitable evaporated cores* are formed; objects similar in size and environmental conditions to our planet. The aforementioned study takes into account class M stars (the smallest size possible, within the main sequence) and small-sized Neptunian planets (equivalent to 10 Earth masses), but the principle could work for other star systems.

However, think again if you thought of simply moving Uranus closer to the Sun and letting it lose its atmosphere! It could take one billion years to lose just the equivalent of 10^{20} kg! Maybe more, maybe less, but we are talking about enormous periods of time [21].

Thus, stripping away the atmosphere would have to involve artificial means, such as atmospheric mining installations and mass drivers or wormholes.

We saw, in (Subchapter **7.2**), that some 1,000 wormholes having 10 m in diameter each and about four centuries are required to ship the hydrogen amount needed by the Venusian ecosynthesis, of 4×10^{19} kg. So, what would it take to transport 8×10^{25} kg of volatile materials in due time? One million wormholes, 100 m wide, would still need 8,000 years to accomplish the task! Even with the help of other mining and launch devices, it would still be an extremely long period of time. And would require huge material costs.

But, even if we manage to do this, it does not spare us from the effort of deviating the planets' orbits towards the Inner Solar System. Uranus and Neptune are too far away from the Sun to host terrestrial life, no matter what planetary engineering techniques we use. And this is also true for their moon systems.

The only advantage of this idea is that it would result in two planets having earthlike sizes and characteristics. Even though the strong gravity on the new Neptune, while not affecting human health, would still be rather unpleasant.

Considering all these, you will understand why I personally and strongly favor the option of helioforming both planets and terraforming their moons. Time will tell if I am right.

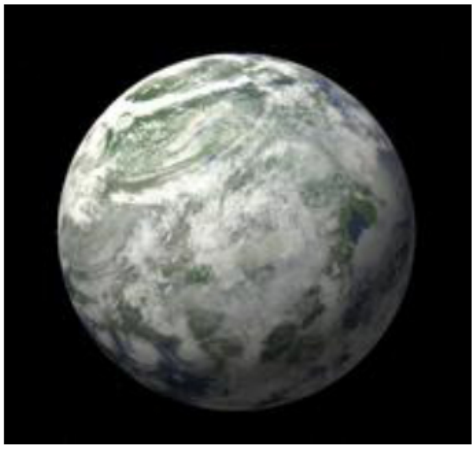

Fig. (8.3). A terraformed Triton [22].

8.2. HOW TO MOVE A PLANET?

We saw that not all the major moons in the Solar System are located at convenient distances from the gas giants they orbit. This way, they could take little advantage of helioformation: they would either get too much light and heat or too little.

If you want to terraform Uranus or Neptune, although I warned you it would be tremendously hard, the distance from the Sun is just too long.

The same problem affects many valuable celestial bodies awaiting us at the edges of the System, in the Kuiper Belt. We are talking about icy dwarf planets: Pluto and its companions (Table **8.2**, Fig. **8.4**). And the table only takes into account a few such objects with a diameter above 650 km. Overall, it is estimated that there are around 35,000 trans-Neptunian objects with a diameter larger than 100 km (and hundreds of millions of smaller ones). Icy worlds, more or less spherical, with eccentric or extremely eccentric orbits, christened after Polynesian, Inuit, Latin and Etruscan deities or simply having numerical indications.

Each one is comparable, in terms of physical and geochemical characteristics, to any of the Jovian and Saturnian moons, with Triton or the main moons of Uranus (Fig. **8.4**).

The practical difference is that these dwarf planets will never get near a star. They are too far away from the Sun and do not orbit gas giants. And they will never get closer by natural means.

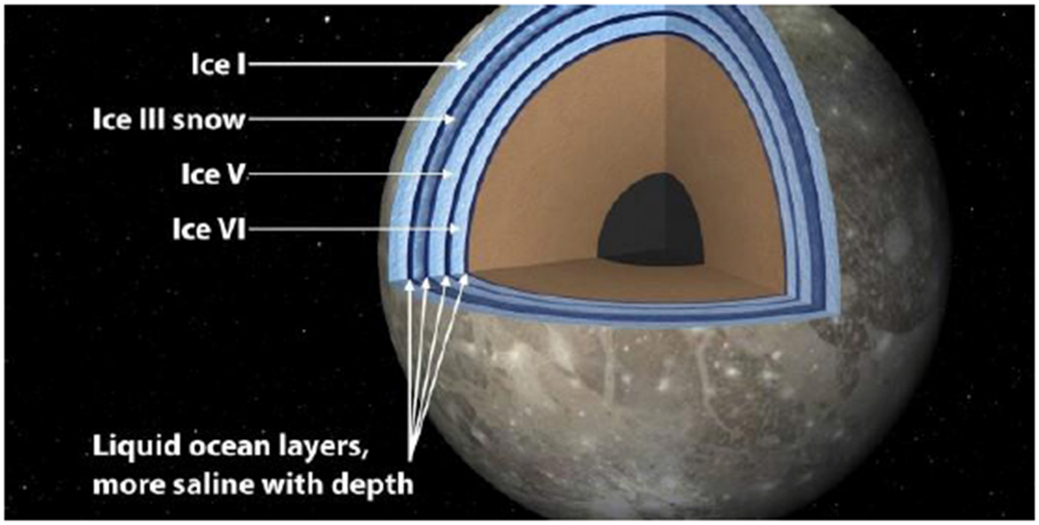

Fig. (8.4). The probable interior structure of Pluto [24].

Table 8.2. Some major trans-Neptunian objects [10, 23].

Planet	Radius (×Earth Radii)	Distance From the Sun (×AU; Average)	Gravitational Acceleration (g)
Pluto	0.187	39.482	0.063
Charon	0.095	Moon of Pluto	0.029
Eris	0.182	67.864	0.083
Haumea	0.122	43.182	0.040
Makemake	0.112	45.430	0.057
Gonggong	0.096	67.471	0.031
Quoaoar	0.084	43.694	0.029
Sedna	0.078	484.438	0.040

(Table 8.2) cont.....

Planet	Radius (×Earth Radii)	Distance From the Sun (×AU; Average)	Gravitational Acceleration (g)
Orcus	0.071	39.174	0.020
2002 MS_4	0.073	42.044	?
Salacia	0.070	42.184	0.016
2014 EZ_{51}	0.060	52.525	?
2002 AW_{197}	0.060	47.042	?
2013 FY_{27}	0.058	58.660	?
2003 AZ_{84}	0.056	39.362	?
Varda	0.056	46.110	0.014
1995 SM_{55}	0.055	41.628	?
2004 GV_9	0.053	42.173	?
2005 RN_{43}	0.053	41.359	?
Varuna	0.053	42.718	?

Although there are factors, such as gravitational waves produced by the Sun or the presence of small amounts of rarefied interplanetary matter, that tend to slow down planetary revolutions and draw them towards the center of the System, they cannot balance the mass lost by the Sun, due to internal nuclear reactions [22 - 24].

This way, planetary orbits are slowly moving farther away from the Sun (by 1.5 cm each year, in Earth's case) [25]!

So, we need some technical means to alter planetary orbits. The main method proposed is that of gravity assist (Fig. **8.5**). Practically, we should play some cosmic-scale snooker!

Let's take Earth as an example! This is because some researchers tried to find ways to move our planet to a farther orbit, for the moment when the Sun will swell and scorch anything in its path (in about one billion years from now).

Earth's current orbital energy is 2.7×10^{40} erg, and to move it away from the Sun by another 0.5 AU, 8.7×10^{39} erg is required. D. Korycansky and collaborators calculated that, if we use an object having 10^{19} kg (four times the mass of Sycorax or one-tenth of Varuna's) as a "tool", we would need one million flybys (one every 6,000 years) at a distance around 10,000 km to accomplish this task [26].

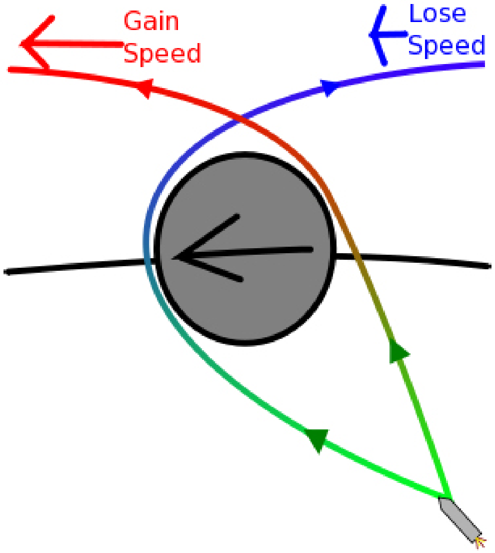

Fig. (8.5). The principle behind gravity assists; it is applied to spacecraft but can also be useful in altering the orbits of asteroids and even planets [27].

Orbital energy is directly proportional to mass and inversely proportional to the orbit's average radius. Pluto has a mass equivalent to 0.002 Earths and an orbital radius of over 39 AU. Thus, its orbital energy is around 1.3×10^{36} erg. And the energy needed to "handle" it drops to 8.4×10^{35} erg per astronomical unit. To bring Pluto into an earthlike orbit, we need 3.18×10^{37} erg.

This means we can use an object 200 times smaller to alter the trajectory (about the size of Ophelia, a 43 km wide Uranian moon) or, even better, a smaller number of flybys (5,000).

But there might be a much better option: to bring Plutonian objects just into the orbits of helioformed gas giants, leaving them to be captured, as new moons. The energy needed to reach Neptune's orbit would be a quarter of that mentioned above, while three-quarters would be required to reach Saturn.

Still, how can we move objects tens or hundreds of kilometers wide in order to use them that way? Again, gravity assists, of course, by using even smaller objects (spaceships, asteroids or maybe, who knows, even tamed mini-black holes; see previous chapters).

One of the main drawbacks of this method is that it is time-consuming and extremely complex, depending on the interactions between large numbers of objects, each with its orbital period.

For asteroids, including those in the Kuiper Belt, or tiny moons, there are also other available means, such as gravity-powered traction, mass drivers or NERVA rockets, as we already saw in (Subchapter **3.2**). This way, we can turn, up to a point, small celestial bodies into massive interplanetary "bolides”, to be used in orbital adjustments.

But these are not the only options. For the same purpose of moving Earth away from the Sun, Colin McInnes proposed building a massive mirror made of space sail material (with a diameter 19.2 times larger than Earth’s; it would require processing a 9 km asteroid), at an angle of 35° to the Earth-Sun line, to concentrate and direct the pressure of solar radiation towards our planet, slowly pushing it away [27, 28].

Obviously, this method is not feasible for large bodies, like Earth, but it can be considered for smaller ones. Still, we should note that radiation pressure varies inversely proportional to the square of distance; thus, on a Plutonian orbit, this means values are 1,600 times lower than on Earth.

Still, it could be used for the smaller moons of Jupiter or Saturn, or to deviate closer asteroids towards the Outer System, to use them for gravity assisting local dwarf planets.

Finally, on small celestial bodies, attaching massive ion thrusters would somewhat help; just keep in mind that they would also consume part of the dwarf planet’s or asteroid’s mass in the process. Thus, a method worth trying, but with caution [29]!

Even so, deviating from the orbit of a dwarf planet would take a long time. To the actual terraformation process (following the same "recipe” as for other cold worlds: Mars, Ganymede, Titan, *etc.*), we should add periods of hundreds of thousands of years, at least. This is if we do not manage to create wormholes and somehow use them in a creative manner.

For now, we do not know how such structures work (naturally, since we can only model them at a theoretical level), yet, besides matter, they could also be used to transmit energy.

From multiple points of view, Gravity seems to behave like light or electromagnetic energy [30]. A wormhole having one end close to a massive cosmic object (Jupiter, for instance) and another orbiting the target object, could transmit some of Jupiter’s gravitational pull and quickly alter the orbit of that asteroid, moon or dwarf planet.

So, maybe someday our descendants will be able to live under the bare sky, on the surface of Pluto and Charon; (Fig. **8.6**) or Sedna...

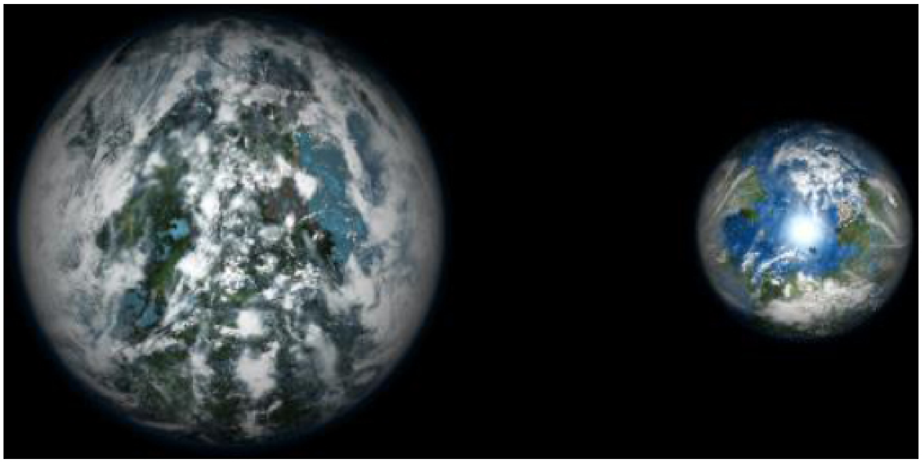

Fig. (8.6). Artistic simulation of terraformed Pluto and Charon [31].

8.3. SOL B?

Right at the edge of the Solar System lies the Oort Cloud. A huge, spherical region, enclosing the entire System, even outside the ecliptic, starting from 2,000 AU and up to over 50,000 AU, or, according to other authors, at over 100,000 AU from the Sun (1.58 light-years!), meaning nearly half of the distance to the neighboring stars (Fig. **8.7**).

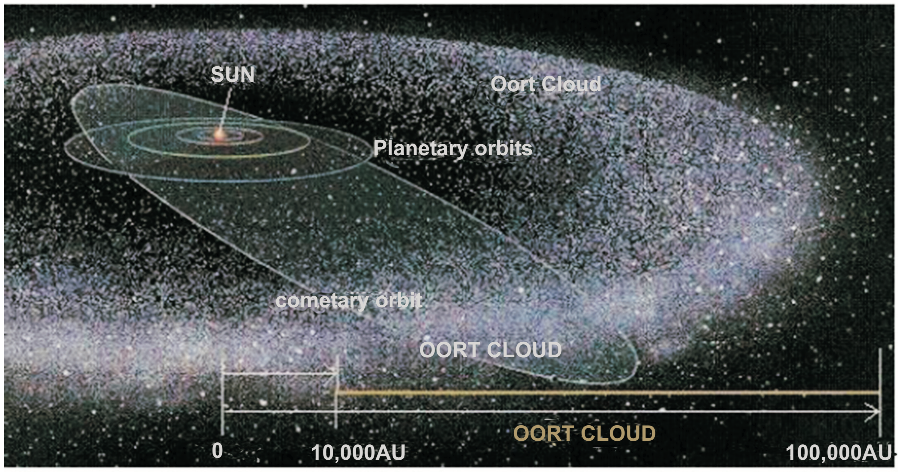

Fig. (8.7). The Oort Cloud [32].

It is an enormous area, hosting trillions of sparse objects (of which, probably, several billion have tens of kilometers in size), mainly cometary nuclei, with a total mass about five times larger than Earth's [31 - 33].

But, even though some of these small objects can prove interesting, if we manage to bring them into a convenient orbit and paraterraform or excavate them to build human settlements, or just use them as a source of water and volatiles, the Cloud could give us much more than that.

Astronomers saw that some objects from the edges of the Solar System simply do not fit there. Sedna's intriguingly eccentric orbit (with a revolution period of 12,000 years!), as well as that of Eris, cannot be explained just by the usual interactions with the Sun and known planets [34].

Some specialists consider that the response could be a massive celestial body, a *brown dwarf*. Its existence would make our system a binary one (obviously excluding future helioformed planets)! Thus, according to usance, it should be named *Sol B*. But its proponents tend to prefer the name *Nemesis*, after the Greek goddess of revenge. This is because its presence could be linked with some past mass extinctions.

This theory is not really new, with the existence of Nemesis being first postulated in 1984. Such a brown dwarf (although some authors even take into consideration a possible white or red dwarf, a proper star, just too "dim" to be easily observable), located at around 1.5 light-years from the Sun, would regularly perturb cometary orbits, sending some of them on a collision course with Earth [35].

But what exactly is a brown dwarf? It is an intermediate object between proper stars and gas giants, having a mass equivalent to 13-75 Jupiter. This mass is large enough to trigger deuterium fusion (even that of lithium, for the most massive ones), but not that of usual hydrogen. This way, they only radiate in the infrared spectrum, meaning thermal energy and very little light (Fig. **8.8**).

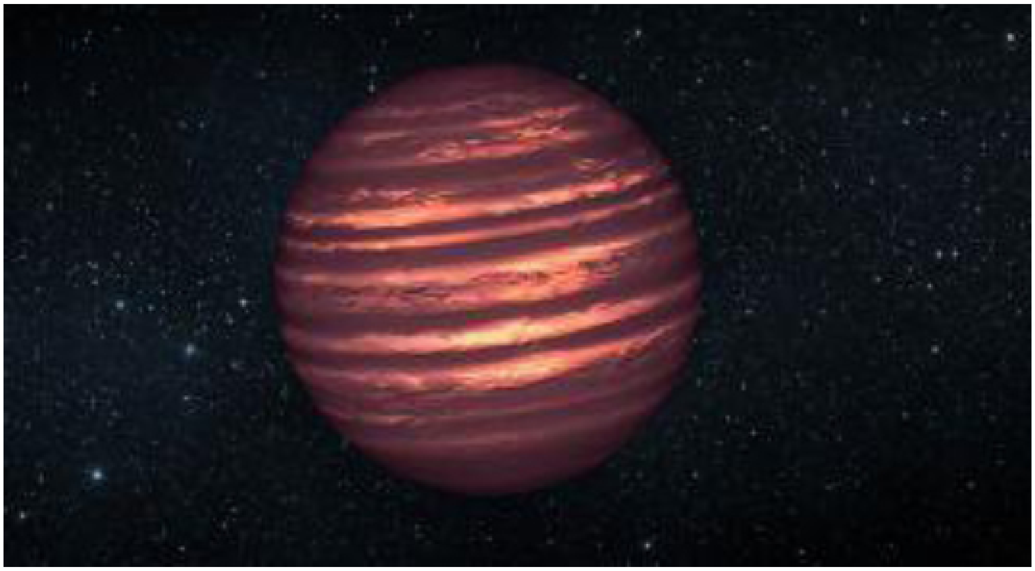

Fig. (8.8). Artistic image of a brown dwarf (of course, no such object was ever observed from a close distance) [36].

They are quite cold for some stars, with an outer temperature sometimes reaching as low as 500°C and with a rather short lifespan, of millions, not billions of years [36].

Like stars and giant planets, brown dwarves have a high potential of gathering various celestial bodies of planetary or subplanetary sizes into their orbit. If Nemesis exists, it is very likely to possess at least some Galilean-type moons (we already know cases of exoplanets orbiting brown dwarves).

And how did we decide to deal with compact accumulations of unignited hydrogen? That's right: with thermonuclear blasts, in order to turn them into proper stars and terraform their moons!

We already discussed, in (Subchapter **5.1**,) the principle behind this method. What may differ in this case are temperature and pressure. They determine the depth reachable by a warhead-carrying probe. We saw that the theoretical limits of current technology are 1,300°C and 200 GPa. This could be enough, or we might need some new materials and screening methods. For now, it is hard to estimate since no brown dwarf was ever studied except a huge distance.

But, until we reach this point, we should know that although there are strong arguments in favor of Sol B/Nemesis, there are also counterarguments based on the total lack of any direct observation, even by using strong infrared telescopes!

Some simulations suggest such a small star would have an unstable orbit.

But some astronomers claim to have the solution for both the eccentricity of Sedna’s orbit and for the lack of any noticeable brown dwarf. Thus, instead of a star, somewhere in the Oort Cloud (not closer than 200-250 AU), there could be a massive planet.

It is not exactly sure what type of planet is involved. While, in 2010, John Matese and Daniel Whitmire announced as quasi-certain the presence of a Jovian-type body [37], having a mass up to 4 times larger than Jupiter’s, other astronomers, such as Konstantin Batygin and Michael Brown, rather support the existence of an ice giant, similar to Neptune or even smaller [38].

No matter what kind of planet it is, astronomers have already found a name: *Tyche*, after the Greek goddess of fate and fortune [39]. But, even more, important than that, such a planet would likely possess potentially inhabitable moons and could be subjected to helioformation.

To ensure that trans-Neptunian space can be full of surprises, some experts say there might be an undiscovered, Mars-sized planet located somewhere in the Kuiper Belt. Since the first hypothesis, in 2017, evidence has been piling up for such a mysterious object (it obviously has a tentative name, *Taraktor*, "perturber”) [40, 41]. And who knows what else might we find in that vast, cold region of our System?

CONCLUSION

Uranus and Neptune, together with their satellite systems, are another valuable target for planetary engineering. While some put forward a strategy of turning the two ice giants into telluric planets, by stripping away their atmospheres, the technical challenges of accomplishing this make these options impracticable.

On the other hand, there are strong clues that helioforming the two giant planets could work, thus creating two more mini-stars and allowing humankind to terraform and colonize their moons, especially Triton. For smaller moons, paraterraforming or massive underground settlements (O’Neill habitats) should be performed.

Techniques such as gravity assist, nuclear thrusters, solar sails or wormhole-transmitted gravity could help us terraform even the coldest objects in the Solar system, by moving them into orbits closer to the Sun or around helioformed gas giants.

Finally, nuclear helioformation could help us take advantage of any eventual gas giant/brown dwarf lurking around in the Oort Cloud.

By applying such strategies, we would complete our expansion in our Solar System and colonize/exploit thousands and thousands of celestial objects.

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CHAPTER 9

Beyond Edges

Indeed, We established him upon the earth, and We gave him to everything a way.
Qur'an, 18:84 [on Prophet Zulkarnain]

Abstract:

Our Solar System represents just a tiny fraction of the Galaxy and the whole Universe. Now we know for sure that many stars host planetary systems, starting with our close “neighbor”, Alpha Centauri.

However, the first problem on the way to our Universe-wide expansion is getting there in reasonable amounts of time. This can only be done by faster-than-light travel, which, in turn, needs “bypassing” normal space-time.

There are some ideas on how we could accomplish these, even if research is still at its beginnings.

Until then, thousands of exoplanets were already discovered. Some of them seem to be rather easy to terraform and settle, while others could also be colonized, by using synergistic means of planetary engineering.

Keywords: Alcubierre drive, Exoplanets, Faster-than-light travel, Habitability, Terraforming, Wormholes.

In our journey through the Solar System, we saw that, despite appearances, there are plenty of celestial bodies that could become new homes for humankind. And we do not only mean colonization, but actual terraformation, worlds where our descendants will be able to live, work and dream under the bare sky, together with other countless life forms brought from our homeworld (Fig. **9.1**).

Of course, this is not really a piece of cake, but nor impossible, even with our current state of technico-scientific knowledge. We saw that this task would be easier for some planets and much more difficult for others. With a little will, we could start right tomorrow and finish terraforming processes in a few millennia. But even small asteroids and moons can be turned, with some effort, into habitable spaces.

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Fig. (9.1). Artistic vision of a fully-terraformed Solar System (most objects above 320 km in diameter were taken into consideration) [1].

The reward is huge-tens of major worlds and maybe thousands or thousands of minor ones. Enough to host human populations ranging up to thousands of billions!

Should we stop there? We have already discussed, in Chapter 1, the demographic and economic consequences of stagnation. Furthermore, we would not be safe! Here, we depend on the Sun and the few helioformable planets. What happens when their life cycle closes to an end, turning them into enormous, killer fireballs?

Fortunately, the edges of our Solar System do not represent an end, but just a frontier toward a new phase. Because beyond them, billions and billions of stars await us, each with its own system of planets, moons, planetoids and asteroids. An infinite array of homeworlds for *Homo sapiens*!

But first, let's get there...

9.1. Faster Than Thought

It is rather hard for a human being to understand, in an intuitive manner, the distances in outer space. Imagine lying on the beach at Mamaia! Down on a beach chair, watching the sea. And now you take a small melon in your hand.

Somewhere in its center, small as a pinhead lies our Sun. And on the fruit's skin, invisible to the bare eye, is orbiting Earth. Uranus lies in the arms of the neighbor on the beach chair in front of you, while Neptune is one row farther.

The closest star system, Alpha Centauri, is another pinhead, very likely having planetary orbits around. But it is located in Eforie-Sud, some 40 km away!

It seems obvious that we need entirely different means of propulsion to cope with distances of an entirely different order of magnitude. Conventional means even the hypothetical Nemesis/Tyche would be impossible to reach in due time. Ion thrusters or VASIMR technology are of little use: traveling for millennia to reach the closest star is not reasonable.

And no idea involving increased acceleration can work. The Universe does not allow speeds higher than the light's (299,792 km/s). And a body having mass cannot be accelerated up to such speeds, and we should not even try it. Why?

Because it would be inefficient – fuel requirements would increase exponentially, and nobody wants to build spacecraft with fuel tanks the size of Earth! Because it is dangerous – interstellar spaces are not completely void and, at relativistic velocities, even the impact with a dust particle or a tiny group of molecules could result in a memorable explosion. And because it lacks finality – once the target reached, the colonists would find themselves completely isolated from their homeworld; a simple bidirectional message exchange with Earth would take more than eight and a half years! And this is from the closest stellar system!

The only way to solve this problem is to completely “bypass” space. To take a shortcut [1].

An interesting concept in Muslim mysticism is *Tay al-Ardh/al-Makan* (“folding up the earth/space”), while Judaism mentions *Kefitzat HaDerekh* (“shortening the way”) [2, 3]. A way of travelling without effectively traversing space, by Divine power and that of one's own mind. Are they just legends or long-lost science? Either way, this would be the path to follow, this time in a more technological manner.

We discussed, in (Subchapter **7.2**), wormholes, as a means to transport things over long distances. Yet, to create a wormhole, we should likely control both ends. So, interstellar travel might require a different solution.

In 1994, Miguel Alcubierre published an article putting forward a revolutionary idea: faster-than-light travel is possible, without breaking the laws of physics. This is because the method he imagined does not imply moving an object through space, but distorting space itself.

More precisely, applying a certain form of energy allows creating a distortion wave that contracts space in front of the object while dilating that behind. Thus, the object would permanently travel enclosed in a space-time bubble, in which its actual movement would not surpass the speed of light in fact, it could not even move at all; (Fig. **9.2**). Velocities (in regard to the universe outside the bubble) could reach, according to the author, ten times the speed of light! A visit to Alpha Centaury could take less than half a year!

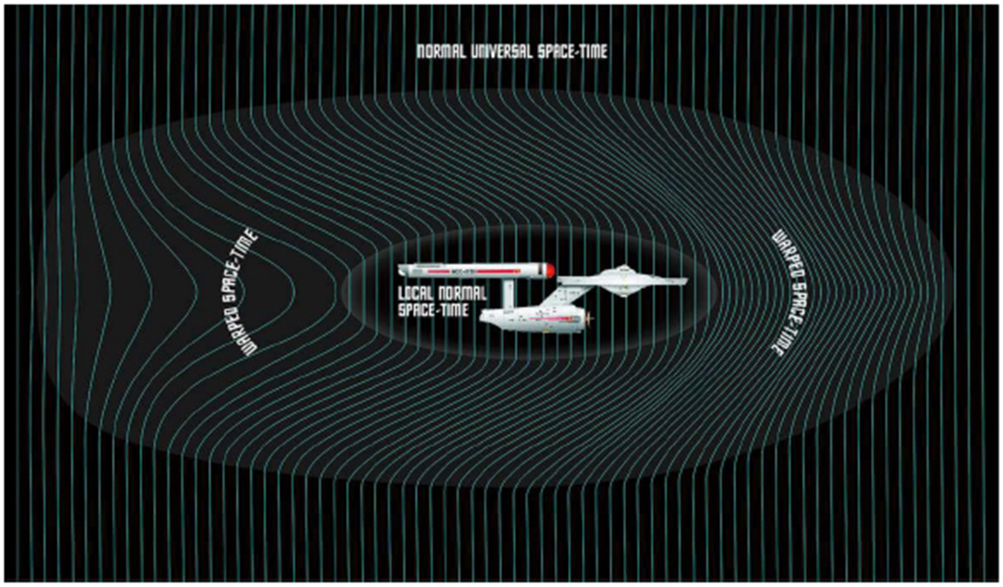


Fig. (9.2). An Alcubierre drive works by contracting and respectively dilating space [5].

Alcubierre, a fan of the "*Star Trek*" series, likened this system to the warp drives. Yet, although he found the necessary mathematical apparatus, he also identified the problems with this method: high energy requirements, the need to use exotic and yet unknown (except at a theoretical level) forms of matter and energy and the difficulty of turning this principle into a real engine [4, 5].

There are also other issues here. The need for some sort of exotic matter to move faster-than-light (there are theoretical solutions, although, for now, they seem to lead to an unfortunate journey ending), the huge amount of negative energy needed to create and maintain the bubble in place (a type of energy that we barely managed to produce in small-scale experiments), but also the accumulation of large amounts of energy inside the bubble, resulting in devastating blasts on arrival [6, 7].

This does not discourage the scientific community, especially since NASA decided to seriously consider studies on the feasibility of such engines. And new research comes with good news.

In the initial model, the energy amount necessary to create the space-time bubble was about the equivalent to that contained in the whole Universe. Other studies have shown the possibility of using energy equal to that generated when reacting masses of matter and antimatter the size of Jupiter (antimatter is the electric opposite of usual matter; when its particles get in contact with those of normal matter, they both undergo an explosive disintegration). By changing the geometry of the distortion field, from a ring shape to that of a "doughnut", Dr. Harold White proves that the energy contained in 500 kg of antimatter is sufficient [8].

Even so, this is a lot of energy. Yet, specialists say that new changes in the topology of the field can further lower the energy requirement, even down to the energy in less than a gram of matter/antimatter. Furthermore, there are solutions to the energy accumulation inside the bubble [9].

In 2012, Dr. White's team pursued some laboratory experiments, to see if, using conventional but very concentrated energy (practically, laser beams), they can create microscopic-scale Alcubierre fields. Unfortunately, the results were inconclusive, due to the low precision of current detection means [10].

However, the Alcubierre drive seems to face some strong competition. We saw that wormholes come with the difficulty of controlling both ends.

But, by using the theory of M. Mansouryar (see Subchapter **7.2**) on interconnected asymmetrical cavities, things could change. By generating a specific type of electromagnetic field, a vehicle could open, maintain and travel through a wormhole, using nonlinear control to navigate inside it.

This way, a spacecraft could produce its own wormhole towards another stellar system, by controlling just the proximal end. With no exotic matter or energy involved.

For now, the concept was never tested, not even at the microscopic scale, but let's admit it, it sounds promising [11]!

No matter what path we choose, research in faster-than-light propulsion is a key direction, essential to the future of humankind. And it needs to continue. Not even a velocity ten times higher than the speed of light is enough to explore and colonize the vastness of the Cosmos!

But what awaits us at the destination?

9.2. A Plurality of Worlds

Up until recently, considering the timeline of our history, anything past the borders of our Solar System was shrouded in uncertainty. Surely, logic always told us that other stars should have their own planets around them, but there was no scientific evidence.

Only in 1988, a team of Canadian astronomers noticed a massive planet orbiting the star Gamma Cephei, a discovery still treated with caution at that time. In 1992, the first planet was confirmed around a pulsar, and in 1995, 51 Pegasi b, was the first cert planet, of Jovian type, orbiting a normal star.

This is because our current technology only allows us to observe exoplanets (as all these bodies outside our System are now known) in a rather indirect manner, by analyzing their gravitational effect or their light spectrum as they pass between their star and the observer.

Such means mostly favor the observation of massive, gas planets. Of those extremely hot or extremely close to their stars. Fortunately, newer and newer observatories, including orbital telescopes Kepler (2009) and TESS (*Transiting Exoplanet Survey Satellite*; 2018), allowed for a real “boom” in exoplanet discoveries [12].

At the moment I write these phrases (October 27th, 2021), NASA officially records 4,538 confirmed exoplanets and 7,854 candidates, distributed across 3,369 star systems. Among these, there is a multitude of worlds, of various sizes and shapes, cold, hot, or having earthlike temperatures, tidally locked to their stars or not, in simple star systems, just like ours, or in others having two, three or even four stars [13]!

Basically, astronomers distinguish about 15 types of known planets. *Telluric planets* resemble ours. *Super-Earths* are mostly “rocky”, but more massive than Earth and its sisters within our System. *Mini-Neptunes*, *ice giants* (or Neptunian planets), *gas giants* (Jovian planets) and *super-Jupiters* are massive worlds mostly made up of lighter elements (Fig. **9.3**).

In turn, Neptunian and Jovian planets can either be cold or hot, depending on the distance to their respective stars and, thus, their atmospheric temperatures.

Neither telluric planets are spared from subclassification. So, besides earthlike ones, we may find c*hthonian* worlds (or *evaporated cores*; remnants of former Neptunian or Jovian giants), *carbonic planets* (with minerals mostly composed of silicon and carbon, instead of silicon and oxygen), *lava worlds* (massive, dense, close to their star, lacking a solid crust) and *ocean worlds* (super-Earths or mini-Neptunes covered by thick layers of water and/or other liquids).

There are small *Trojan planets*, that accompany larger ones, on common orbits and *rogue planets*, expelled from their native stellar systems and that freely wander through interstellar space [14]. Also, the first exomoons were found: in 2019, astronomers observed some Jovian or super-Jovian bodies orbiting even larger gas giants. This is not really the image commonly associated with the term “moon”, but it is a beginning (we should not be surprised if each of these giant “moons” will prove to have its own system of moons!) [15].

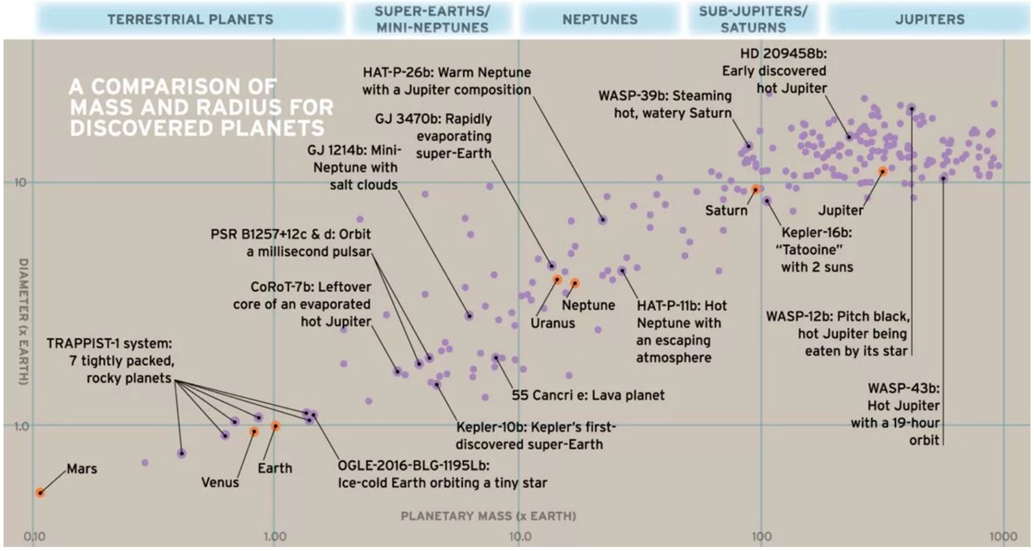


Fig. (9.3). Size classes of exoplanets, with some noteworthy examples [14].

Equipped with Alcubierre drives or wormhole generators, we will be able to explore, colonize and terraform them. We would create new homes for humankind and a perfect sink for the demographic growth of our own Solar System, new sources of raw materials, and agricultural and industrial centers. So, let's see some of the most interesting planetary systems discovered until now!

A perfect target for space colonists is the Gliese 581 system. Located at about 20.5 light-years from us, it has a red dwarf star at its core. At first glance, it would not look too welcoming due to its dim light.

Yet, orbital radii seem well-proportioned enough to give the planets within the system adequate sunlight.

Gliese 581e is a telluric world, twice more massive than Earth, located at just 0.033 astronomical units from the star, with a revolution period of 3.15 days.

A bizarre, probably very hot and tidally-locked planet, somewhat equivalent to Mercury.

Gliese 581b is a Neptunian planet located at 0.014 AU from the star, with a mass 16 times larger than Earth's [16].

Gliese 581c has the equivalent of five Earth masses and seems to be a bit too hot to be in the naturally habitable zone. A massive Venus!...

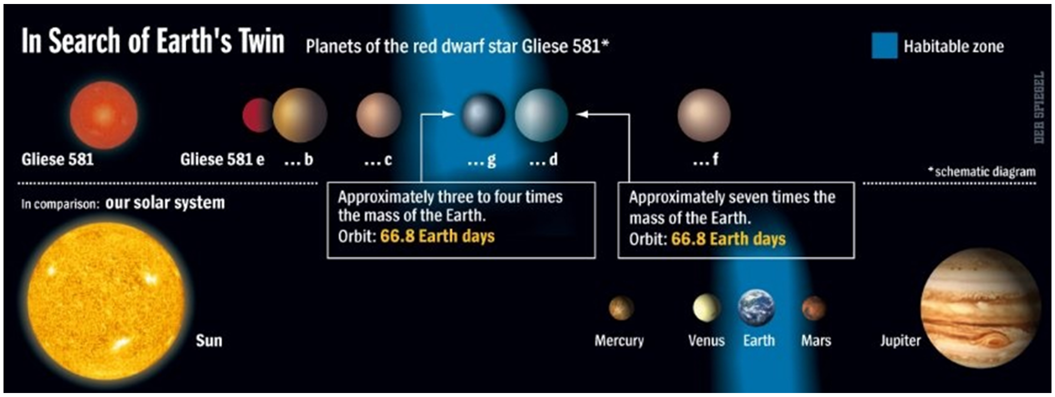
Gliese 581g is still telluric, four times more massive than Earth, at 0.146 AU from the star and with a revolution period of 37 days, a mild climate and, possibly, an atmosphere.

Gliese 581d has seven-eight times Earth's mass and might or might not have a reasonable climate, depending on the still unknown atmospheric composition.

Finally, Gliese 581f is similar to the latter, but significantly colder (Fig. **9.4**) [17].

Five telluric planets in a single system (this if there are no other, yet undetected ones) is a fortunate coincidence. And the Neptune-like Gliese 581b could have some moons, if it really resembles gas giants in our System.

Of course, not all those planets are inside the habitable zone or, as astronomers call it, the *Goldlilocks zone* (after a character in a British fairy tale, that sneaks into the home of three bears, while they are away, sits on their chairs, eats their porridge and sleeps in their beds; the process is rather time-consuming since she has to choose which of the three rather different bears' chairs, blankets and porridge plates suit her).


In Search of Earth's Twin
Planets of the red dwarf star Gliese 581*
Habitable zone
DER SPIEGEL
Gliese 581
Gliese 581 e
... b
... c
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... d
... f
*schematic diagram
In comparison: our solar system
Approximately three to four times the mass of the Earth.
Orbit: 66.8 Earth days
Approximately seven times the mass of the Earth.
Orbit: 66.8 Earth days
Sun
Mercury
Venus
Earth
Mars
Jupiter

Fig. (9.4). Gliese 581 star system, compared to ours [16].

But, it should be noted that this concept implies a naturally habitable region long term! It does not take into account potential terraformation and climate control, through atmospheric engineering! It is possible that each of the five planets could be converted into a habitable world: if we could someday live on Venus, Mercury or Ceres, then why not on Gliese 581e or Gliese 581c?

There is still the problem of planetary mass. Surface gravitational acceleration is, of course, directly proportional to it. Yet, it is also inversely proportional to the square of the radius, a parameter still unknown for exoplanets. A radius twice as Earth's would make the excess gravity of the most massive of the aforementioned planets less than 75%. At 1.5 Earth radii, we are talking about 3.11 g, for the outer planets (including Gliese 581d), and just 1.77-2.22 g for Gliese 581g and Gliese 581c.

Research in plant growth under simulated hypergravity led to mixed results, depending on each species. This way, (intermittent) exposure to 7 g can stimulate early seed germination in carrots or arugula [18]. On the other hand, similar experiments conducted on rice (at over 500 g, but with short exposures) led to reduced biosynthesis of chlorophyll pigments [19].

Anyway, experts consider that the effects of moderate hypergravity (2 g) on tissular growth are less pronounced than those of low gravity, of Martian type, for instance [20].

As for humans, astronauts go through 3.2 g accelerations at each launch and 1.4 g at each atmospheric reentry. Experimental studies are conducted on the effects of up to 12.5 g hypergravity. The main consequences are mostly felt in corporeal fluids (thus, on the cardiovascular system, which needs to adjust its blood-pumping capacity) and vestibular system. Nausea and even fainting are among the most severe effects [21].

Exposing rats to periods of hypergravity (4 g) affected their hippocampus, with possible effects on their memory. An increased serotonin secretion may occur, leading to hypophagia.

On the other hand, exposing rhesus monkeys to longer periods of hypergravity (two weeks at 2 g) led to positive effects on bone tissue: an enhanced synthesis of collagen and increases in trabecular tissue volume and mineralization.

Moderate hypergravity (2 g) did not induce negative effects on the skeletal muscle system in mice. Still, inhibition can occur in cardiac muscle, at 15, but gradual exposure can counter it. Finally, the influence of hypergravity on the immune system is yet insufficiently understood [22].

Briefly, with a little training, *Homo sapiens* could even colonize the high-gravity worlds (2-3 g) in the Gliese 581 system. Maybe it will not be very pleasant from the beginning, but our organism can adapt.

Another interesting planetary system is TRAPPIST-1 (from *Transiting Planets and Planetesimals Small Telescope*). It is located some 40 light-years from Earth, around a red dwarf star that is very small and cold, even for its class.

The system (Fig. **9.5**), older than ours, features no less than seven telluric planets, with characteristics rather similar to Earth's! Among them at least three (TRAPPIST-1e, f and g) seem to be located within the habitable zone.

They all have a high content of rocks, and seem to possess atmospheres, and there are clues that they might also contain water, up to 5% (250 times the water amount on Earth).

More precisely, the inner planets, TRAPPIST-1b and c, are very close to their star and observations seem to indicate some dense atmospheres (but not like the hydrogen-rich ones on Neptunian planets!). They might be somewhat similar to Venus, although the former is so hot that it could not even maintain a reflective cloud system like that of Venus [23].

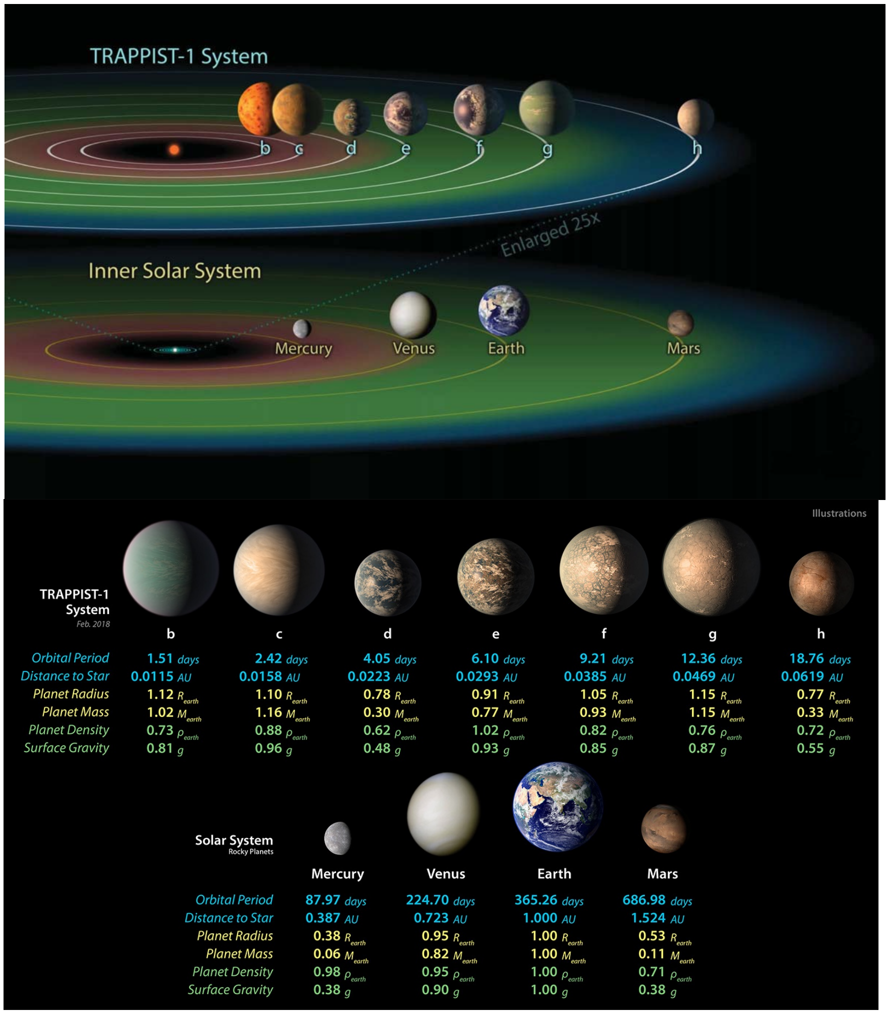
TRAPPIST-1d also seems Venusian. Its low density indicates a high content of volatile compounds (a thick atmosphere or, maybe, an ocean). The next one, TRAPPIST-1e, seems the most “earthlike”, with a mild climate and, according to some estimates, lots of liquid water and high oxygen content (due to the photochemical decomposition of water) [24 - 26].

TRAPPIST-1f and g are also habitable, if we consider temperatures, but colder and probably, have large amounts of ice. The last planet is a bit outside the Goldlilocks zone and seems to be covered by ice [26].

By analyzing (Fig. **9.5**), we notice an important feature of all these planets: it seems they all have surface gravitational accelerations similar to that on Earth, between 0.48 and 0.96 g. Thus, atmospheres are not easily lost in space, nor will the colonists feel excessively “pulled down” by gravity.

For the first three planets, we would probably need to apply terraforming techniques like those discussed in Chapter 7, for Venus. We do not know their atmospheric composition, but excess gases need to be removed (through chemical conversion and/or sequestration into lithospheric minerals), while the rest of the atmosphere needs to be given an anti-greenhouse effect (using reflecting clouds, *etc*.), to adequately cool them.

On the three already habitable worlds, especially on TRAPPIST-1e, we may face some excess water (or not, as there are also opposing views!). An integrally oceanic world is not the best option for settlement. We might need to drain this excess, through wormholes or ballistic means, towards planets with water deficit.



TRAPPIST-1 System Feb. 2018

	b	c	d	e	f	g	h
Orbital Period	1.51 days	2.42 days	4.05 days	6.10 days	9.21 days	12.36 days	18.76 days
Distance to Star	0.0115 AU	0.0158 AU	0.0223 AU	0.0293 AU	0.0385 AU	0.0469 AU	0.0619 AU
Planet Radius	1.12 R_{earth}	1.10 R_{earth}	0.78 R_{earth}	0.91 R_{earth}	1.05 R_{earth}	1.15 R_{earth}	0.77 R_{earth}
Planet Mass	1.02 M_{earth}	1.16 M_{earth}	0.30 M_{earth}	0.77 M_{earth}	0.93 M_{earth}	1.15 M_{earth}	0.33 M_{earth}
Planet Density	0.73 ρ_{earth}	0.88 ρ_{earth}	0.62 ρ_{earth}	1.02 ρ_{earth}	0.82 ρ_{earth}	0.76 ρ_{earth}	0.72 ρ_{earth}
Surface Gravity	0.81 g	0.96 g	0.48 g	0.93 g	0.85 g	0.87 g	0.55 g

Solar System Rocky Planets

	Mercury	Venus	Earth	Mars
Orbital Period	87.97 days	224.70 days	365.26 days	686.98 days
Distance to Star	0.387 AU	0.723 AU	1.000 AU	1.524 AU
Planet Radius	0.38 R_{earth}	0.95 R_{earth}	1.00 R_{earth}	0.53 R_{earth}
Planet Mass	0.06 M_{earth}	0.82 M_{earth}	1.00 M_{earth}	0.11 M_{earth}
Planet Density	0.98 ρ_{earth}	0.95 ρ_{earth}	1.00 ρ_{earth}	0.71 ρ_{earth}
Surface Gravity	0.38 g	0.90 g	1.00 g	0.38 g

Fig. (9.5). TRAPPIST-1 planetary system, compared to our own (the green area is the estimated habitable zone) [14]; the main characteristics of its planets [23].

Cooler planets, including TRAPPIST-1h, might be more similar to Mars (in the best-case scenario) or to the Jovian moons (in the less fortunate scenario). Artificial warming, atmospheric engineering, greenhouse gas production and, in extreme cases, deviating its orbit closer to the star would be de adequate ecosynthesis methods.

By analogy to Callisto and knowing their density, it seems very likely that, within the crusts of the latter planets, rocks and ice are not strictly layered, thus allowing landmasses to exist after global warming.

Finally, there are some other problems to solve. All or at least most planets in the system are likely tidally-locked to their star (with one hemisphere permanently facing the star). We already know the solution: Dyson spin motors and controlled impacts.

Ocean tides could also be extreme. Finally, ionizing radiation exceeds any known case in our Solar System. This is due to internal fusion processes involving heavier nuclei, specific to red dwarves, but also to the short distances inside the system.

Especially TRAPPIST-1e, the most habitable world of the system, seems to be also the most hit by radiation, with an incident particle flux one million times higher than that on Earth. To ensure protection, we need an artificial magnetosphere a hundred times stronger than our planet's [27]. This is quite technologically feasible, as we saw in previous chapters.

Gliese 667 system (23.6 light-years from Earth) is a triple one, and Gliese 667C is a red dwarf having seven planets (probably all of them are either telluric or super-Earths) orbiting around. Three of them are located inside the naturally habitable zone and have general characteristics rather similar to our planet's (Fig. **9.6**).

They are all, probably, tidally-locked to their star. Gliese 667Cc, the most massive of the three habitable planets, has a surface gravity of around 1.1 g [28].

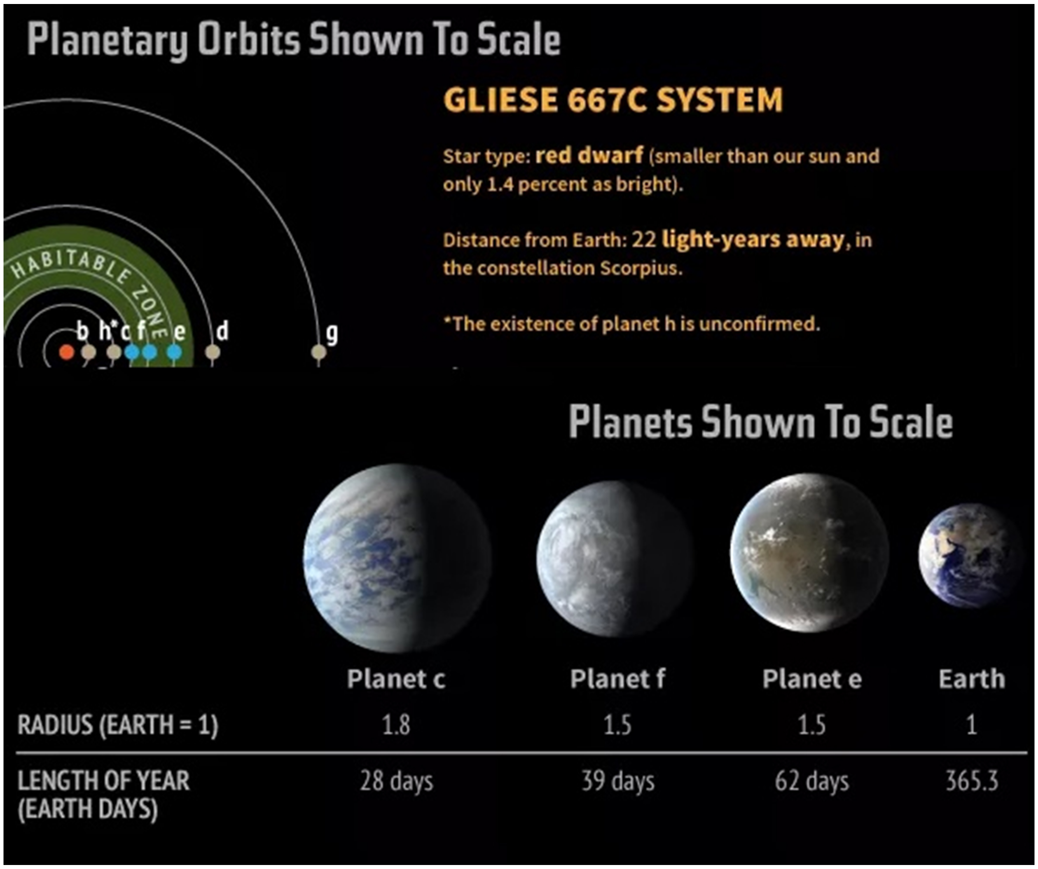
The situation seems to be analogous to that in the systems previously described. All planets will need Dyson motors in order to be successfully terraformed. Inner planets would need ecosynthesis and caeliforming techniques similar to those applied on Mercury and Venus, while outer ones would follow the Martian scenario.

Luckily, the three habitable worlds will require only minor changes.

Kepler orbital telescope also allowed observing a plethora of planets that seem to be in the Goldlilocks zone. Kepler-186f, for instance, is located 500 light-years from us and is very similar, in size, to Earth [29].

Kepler-22b is 600 light-years away, with an average temperature of around 22°C, but a diameter 2.4 times larger than Earth's; thus, it probably, massive and with quite an unpleasant gravitational pull [30].

Kepler-452b is rather distant (1,400 light-years from Earth), old (6 billion years), rocky and massive (with a diameter 60% larger than our planet's), but earthlike when considering surface temperature, year length and, probably, gravitational acceleration [31].



GLIESE 667C SYSTEM

Star type: **red dwarf** (smaller than our sun and only 1.4 percent as bright).

Distance from Earth: 22 **light-years away**, in the constellation Scorpius.

*The existence of planet h is unconfirmed.

	Planet c	Planet f	Planet e	Earth
RADIUS (EARTH = 1)	1.8	1.5	1.5	1
LENGTH OF YEAR (EARTH DAYS)	28 days	39 days	62 days	365.3

Fig. (9.6). Gliese 667C planetary system and the characteristics of the three habitable telluric planets [28].

Kepler-442b (1,100 light-years from us) is considered, on a scale designed by astronomers, as "more habitable than Earth"! [32] And Kepler-1649c, a somewhat "closer" planet (300 light-years), has 1.06 times the size of Earth, while receiving from its star some 75% of the incident sunlight on our planet. It also has a "sister", Kepler-1649b, still telluric, but most likely having conditions similar to those on Mercury or Venus [33].

But we do not need to go too far away to find valuable planets! Alpha Centauri C (our neighboring star system, located at just 4.3 light-years, is a triple one), a red dwarf close to us, seems to harbor at least two planets!

Proxima b, discovered in 2016, has a mass 30% larger than Earth's, while the distance to its star theoretically allows the existence of liquid water and a climate somewhat similar to the terrestrial one, except for the fact that it is either tidally-locked, or has an extremely slow, Mercury-style rotation rate [34].

Proxima c is a Neptunian object (having about half the mass of Neptune) and, for the moment, very cold (-200°C, without knowing eventual warming/cooling effects due to atmospheric composition), orbiting the star at a long distance [35].

Keep in mind that not just the widely-considered “habitable” planets are of interest! As we saw, there are technical solutions to bring life even on hostile planets like Mercury, Venus, Mars, the Moon or dwarf planets.

Obviously, the enormous diversity of exoplanets will test our imagination and inventiveness. How could we terraform an ocean world? What about a hot lava planet?

Maybe by draining the excess water of the former towards the latter, by using wormholes!

On dry, sterile planets lacking an atmosphere, we should import the necessary volatile resources, eventually, from Venusian or ocean planets, where such compounds are in excess.

What about a carbon planet, having rocks of silicon and carbon instead of the silicates we are used to? Do they have the necessary resources to support a biosphere? Will it affect the development of those organisms (diatoms, radiolaria and even grasses) whose cells naturally feature valves, shells or other various accumulations of silicon oxide?

Finally, besides telluric planets, there are gas and/or ice giants (actually, most of the exoplanets discovered so far). Including the bizarre case mentioned above, that of Jovian bodies orbiting other Jovian bodies.

What do we know about these types of celestial objects, having in mind the four examples in our Solar System? We know that they tend to gather lots of moons around them! Of which some have planetary sizes. And we also know (see Chapter 5) that giant planets can be subjected to helioformation.

This way, each star system could host its own subsystems, with numerous satellites transformed into habitable worlds. An infinity of realms awaiting us!

CONCLUSION

Terraforming and colonizing the various planets, moons, planetoids and asteroids in our Solar System would make room for a flourishing, advanced civilization, with tens of billions of people.

However, our cosmic expansion must not end there, in order to safeguard the future of our species. Most stars, in our close neighborhood or not, in our Galaxy or not, have their own plethora of planets and other potentially habitable objects, of which we have just seen a glimpse.

For this massive and necessary endeavour, we first need to find adequate means of long-distance space travel. This is why researching wormholes, Alcubierre drives, and other solutions is a top priority. Furthermore, such means of instant travel would greatly help our terraforming projects.

Once arrive there, we should basically apply the same planetary engineering techniques we learned from our own star system. This is the way to turn our civilization into a truly universal one!

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CHAPTER 10

Ethical Issues

We'll never be anyone here. We won't be human here. We won't do anything new. We won't grow. We get sick here. We're degenerating. There's no air.There's no room here. It's cramped in here.

Artyom "Dark" (character of the Metro 2033-35 series, by Dmitry Glukhovsky)

Abstract:

Space settlement, while drawing much support from public opinion, also has its critics. They bring various counterarguments, from the need to "fix" Earth's problems first to the use of nuclear explosives and military devices, which might go against international treaties. However, the main argument is the desire to preserve eventual life forms, including microscopic ones, that might be encountered in the C.

Here, we argue that the highest likelihood is that of life scarcity in our Universe. Life forms are, most probably, rare, usually microbial and living in environmental niches which would not be affected by terraforming. Intelligent life should be even much scarcer.

Furthermore, we argue that space expansion is not just a desire but an imperative for preserving and growing our species and our entire Biosphere.

Keywords: Alien life, Conservationism, Ethics, Intelligent life, Extremophiles, Terraforming, Transpermia.

Beyond this endless Universe, there is nothing. Or is it? Anyway, we have no idea yet. So that this book may well end here.

And I would end it if I did not know that human expansion into space has its critics. Even if, instinctively, the perspective of our descendants creating thousands and thousands of worlds teeming with life, settling them and expanding indefinitely, probably charms the minds and hearts of most readers, we must accept that there are also opposing views.

Dan Răzvan Popoviciu
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From the first moment *Homo sapiens* left his ancestral land, wherever that is, spreading all over the Globe and radically altering his environment and his way of life, he had this thought: shouldn't he rather "clumped" in his native homeland?

Of course, it's a joke! No, for millennia, humans did not have such dilemmas. Fortunately, I say, since otherwise, there would have been no progress. You would not read this book, which would have never been written (like no other book would have been written or read, in general). We would be living in an eternal Paleolithic!

The issue of "slowing down" or "temperating" human progress and expansion, as an intellectual solution to the problems of humankind, is a radical response to the sometimes reckless actions of contemporary civilization: pollution, destruction of natural habitats, altering atmospheric composition and climate, war, nuclear weapons testing. It is mostly connected to "Green" politics and thought.

And this environmentalist criticism also extended to human activities in space. You have surely noticed this kind of discourse, in offline or online media.

We discussed, in Chapter 1, the negative and damaging consequences of stagnation, be it demographical or economical. And the solutions put forward for "colonizing Earth" in Chapter 2 always mean a durable development that harmoniously integrates urban, agricultural and natural ecosystems. A planet that is populous and economically exploited at its maximum potential, but is still "green". This is because a chaotic and destructive development, such as that in the last decades, threatens not only wild species, the result of millions and millions of years of evolution, but also the actual health, wellness and prosperity of our own kind of our descendants.

If these ideas will probably not cause much controversy, the situation dramatically changes when we discuss space colonization.

A rather frequently heard but easy-to-respond counterargument is the following: our planet already has plenty of problems; why not solve them first, and then think of other worlds?

The answers are pretty obvious. First, solving social, economic and ecological issues here on Earth does not contradict our cosmic expansion.

Second, as we saw in Chapter 1, colonizing their worlds is essential to the future and even the continuity of humankind! Focusing on one planet only makes us vulnerable and leads to certain extinction. The farthest point reachable is the catastrophic dilation of the Sun, in about one billion years: humans will definitely not survive such an event. But other cosmic cataclysms are lurking around the corner and threatening to send our entire species into oblivion.

Unfortunately, the Universe does not wait for us to solve our problems, and, as we also saw, the process of rendering other worlds truly habitable could take entire millennia!

Yet, the most important and widely-debated argument is that of our interaction with other possible life forms in the Universe. Is there life outside Earth? This is a brief and simple question that is impossible to answer in a precise manner for now.

It can be subdivided into two secondary questions. Are there life forms (of any kind, including microbial ones) outside Earth? But is there intelligent life outside our planet?

Furthermore, there is another way to subdivide each of these questions. Is there life (intelligent or not) independently evolved from the terrestrial one? Is there life (intelligent or not) of terrestrial origin (or sharing a common origin with the one on Earth) on other celestial bodies?

Let's start with the first of these four questions! Is it possible that, somewhere in this Universe, life appeared independently from that on Earth? Since the Cosmos is huge, this is very likely. However, the main issue here is its frequency, which is how likely it is to find alien life, at least within our close neighborhood.

The trouble here is that we only have one example to start with: life as we know it here, on Earth, with its specific biochemistry.

We can just imagine alternative forms of life chemistry. Some researchers already did! For instance, organic structures are based on silicon (or, at least, a mixture of carbon and silicon as a skeletal formula), or ammonia as an intracellular solvent, instead of water [1, 2].

Yet, there is a constant here: organic chemistry, mainly based on light elements, is the only one able to ensure the complexity and plasticity indispensable to life. And there is one more constant: thermodynamics. Towards absolute zero (-273.15°C), thermal agitation progressively slows down, until it completely ceases. And at high temperatures, a high thermal agitation causes various compounds to dissipate, evaporate or melt.

Life is an endless sequence of chemical reactions. Thus, no matter the exact structure of the compounds involved, a temperature too low or too high would probably not allow any kind of life form. Hard to imagine metabolic processes with inert chemicals or instantaneous decompositions!

We often hear of micro- or macroorganisms able to tolerate extreme living conditions. Species of *Bacillus* and *Geobacillus*, for example, can withstand exposures (even rather long ones) to over 100°C or well below the freezing point. Or pressures above 800 MPa. Radiation levels 10-50 times higher than normal (even more, as we saw in the case of *Deinococcus radiodurans*; see Subchapter **4.2**) or extreme pH variations [3].

Some researchers claim to have "resuscitated" bacteria found in amber, ice lenses or water droplets inside salt crystals after 250 million years [4]! Similar extreme resistance features can also be found in some fungi, lichens (especially crustose ones, living in arid regions) or plant seeds [5].

Finally, maybe the most "popular" organisms with a remarkable tolerance to extreme environmental conditions are tardigrades (water bears): tiny invertebrates, very widespread as a taxonomic group (marine and fresh waters, wetlands, but also deserts and polar areas), feeding on microalgae, lichens and mosses (Fig. **10.1**).

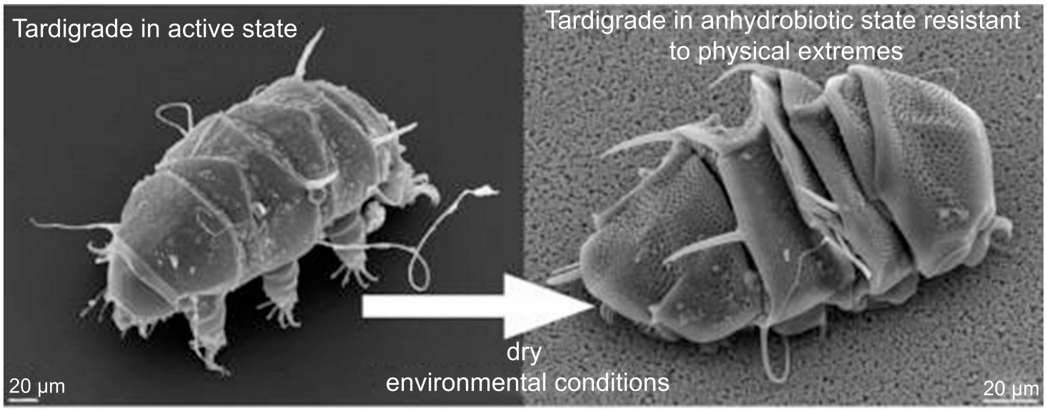
Tardigrade in active state
Tardigrade in anhydrobiotic state resistant to physical extremes
dry environmental conditions
20 μm
20 μm

Fig. (10.1). Tardigrades: champions of resistance to extreme conditions, in their active and cryptobiotic state [8].

Subjected to laboratory tests, some resisted being immersed for 21 months in liquid air (-190°C), 26 hours in liquid nitrogen (-253°C) and up to 8 hours in liquid helium (-272°C). Some species can survive one hour at 70°C, or a few minutes at 151°C. They can withstand exposure to alcohols and methyl bromide, hydrostatic pressures up to 600 MPa and normally lethal doses of ultraviolet, gamma or X-rays [6, 7].

Yet, there is an important thing to note here: tolerating or resisting extreme conditions does not mean being able to live permanently under such conditions! The bacteria mentioned resist as spores. Other organisms turn to cysts. This is, somewhat the case with tardigrades.

In these situations, component cells radically change their internal structure: they eliminate water (to prevent destructive lesions), concentrate sugars (trehalose) or lipids, in order to preserve the ultrastructure of proteins and other macromolecular compounds during dehydration, cover themselves with rigid and hardy coatings and slow down their metabolism to extremely low rates. It is a state called *cryptobiosis* or *anabiosis*, that can last for a long time but not indefinitely [3, 7]!

An organism undergoing cryptobiosis is inactive: it does not feed, photosynthesize or reproduce. And extending the unfavorable living conditions beyond a certain time limit will make the spore, cyst, *etc.*, lose its viability: the organism dies. So, even though the tolerance ranges of living matter can be quite impressive, the limits that allow it to stay constantly active are much narrower!

Thus, it would be rather reasonable to exclude worlds that are either too cold or too hot, those with too eccentric orbits (leading to extreme temperature variations) and gas giants, with a chemical composition unsuitable for living.

But even habitable planets do not necessarily maintain the same environmental conditions in the long term. We saw that Mars and Venus once had climates similar to Earth's. Nowadays, one is a frozen desert, while the other is a hot inferno. Another proof that the Universe is a dangerous place!

And, on planets that still keep their favorable conditions, how likely is for life to develop?

You will find as many answers as people are concerned! They range from the optimistic "*where there is water, there is life*", to the absolute uniqueness of terrestrial life. There are arguments on both sides, but one, in particular, is a rather strong one.

We already know a telluric planet, with a mild climate, liquid water and a suitable atmosphere. It's Earth. Of course, it hosts life!

Yet, all living organisms derive from a single common ancestor. There is a single phylogenetic line, abundantly branched, linking all known life forms: bacteria, archaea, and eukaryotes (including plants and animals). How do we know that?

Easy: all these organisms use deoxyribonucleic acid (DNA) to store genetic information (and ribonucleic acid, RNA, to mediate its translation into proteins). Furthermore, they all use the same basic nucleotides: adenine, cytosine, guanine, thymine, plus uracil (in the RNA, rarely found in DNA). This is even if there are lots of other possible nucleotides, some even present in the genetic material but rarely used by all living beings (how many times have you heard of methyladenine, methylguanine *etc.,*?) [8, 9].

Even more, the genetic code, meaning the way DNA/RNA are being read and "translated" into aminoacid sequences, stays mostly unchanged, in the whole tree of life [10 - 11]!

Biologists named this common ancestor of life "LUCA" (*Last Universal Common Ancestor*). It was definitely not the first organism on Earth, but it is the one that gave birth to all those currently extant. Genetics and phylogeny show it was a prokaryote, thermophilic organism, probably living in marine thermal vents, anaerobic and autotrophic, preferring environments rich in carbon dioxide, hydrogen and iron [12 - 14].

And this aspect is rather significant: a planet having all the ingredients needed to support life, but where life emerged only once in billions of years of history!

As a postgraduate student, I studied the microbiota of marine sediments. Each cubic centimeter hosts hundreds of millions, or even billions of bacterial populations. If you take some fine sand or mud from the bottom of a still water body and look at it, you will immediately notice its texture: much of its mass is decaying organic matter. But even the dense microbial community inside needs lots of time to decompose all those chemicals.

This organic matter also includes dead m-icroorganisms, practically cell fragments, since not all the bacteria we see directly are really alive [15]! So, there are, here on Earth, environments with huge amounts of undecayed organic compounds, including cell "components" and, still, new life does not spontaneously emerge! A clue of life scarcity in the Universe. It is very likely that life appeared in other places, too, just that it should be rather rare!

A logical consequence is the scarcity of intelligent life, which independently evolved outside Earth. We often take life evolution towards complex and intelligent forms for granted. We represent the natural evolution process as a line starting from LUCA, with various collateral branches, but going straight to *Homo sapiens*, bipedal, proud and muscled (a representation of what some witty biologists call "*the schwarzeneggerization of life*")!

Yet, for most of Earth's history, the dominant life forms were m-icroorganisms. Even among multicellular organisms, few lines led to large-sized beings, with an active way of life (to live on photosynthesis, decomposition or filtering organic matter from water, one does not need a performant nervous system) [16].

Even fewer phylogenetic lines led to actual intelligence. A dolphin, a dog, a cat and, of course, an ape, are intelligent. Likewise, some birds and cephalopods (octopuses and relatives). Thus, some mammals, birds, cephalopods and that's all. And intelligence has various degrees; it does not necessarily imply the capacity to create an organized, technological society.

Then, intelligence can have multiple forms. There is no doubt that our Neanderthal "cousins" were smart. Yet, their intelligence manifested itself in ways we do not really understand, but that blocked the progress of this species. In hundreds of years of existence, Neanderthal culture did not evolve much. Most likely, the brains of our relatives were not so efficient in processing and integrating different types of information [17].

We must keep in mind that there is absolutely no mechanism to create an imperative evolutionary pressure towards increasing complexity or intelligence. This is because, although they both have some advantages, they also come along with significant drawbacks: energy costs, vulnerability to extreme environmental factors *etc.,* [16].

If we agree that it is improbable to find independently evolved extraterrestrial life in our proximity and even less likely to find a Universe teeming with alien civilizations, there is an entirely different discussion on the third question. Is there (microbial) life of terrestrial origin on other planets?

While it may seem odd, it makes sense! Eruptions or asteroidal impacts can eject amounts of planetary mass into the Cosmos. And, from there, it can reach other planets: after all, Martian meteorites are found on Earth, for instance.

But what if those ejected rocks carried the germs of life? Spores, cysts, seeds *etc.*? We are not talking about *panspermia* (not to mention *directed panspermia*) which is hard to imagine, considering the enormous distances between star systems (see Chapter **9**).

We are talking about a "local" and entirely natural transfer of some life forms between celestial bodies within the same planetary system, a process called *transpermia*.

Various studies show that it is theoretically possible: there are organisms (especially bacteria) that could survive the ejection, a more or less long period of travelling through space, atmospheric reentry and impact.

Of course, this phenomenon is not very likely to occur, but over long periods of time, it becomes possible. Keep in mind that, up to a few hundred million years ago, Venus and Mars were as habitable as Earth. We cannot rule out the possibility that life emerged on any of these three planets and then propagated to the other two, or even to other planets and moons in the system [18 - 20].

In 1996, some electron microscopy images made a splash in mass-media. We are talking about traces of biological structures, possibly microfossils, next to magnetite particles rather specific to microbial life than to natural processes. All from ALH 84001, a meteorite formed some 4 billion years ago, on Mars, and fell in Antarctica 13,000 years ago (Fig. **10.3**).

Of course, opinions are divided, and many researchers support the abiogenic origin of these formations through wearing some clay minerals and magnetite precipitation at high temperatures, while others still consider them as potential fossils [21, 22].

And Mars is not the only planet where potential fossils were reported. In 1999, two biologists, Stanislav Zhmur and Lyudmila Gerasimenko, announced the discovery of such biogenic structures in rocks brought from the Moon, twenty years earlier. According to the two scientists, some microfossils are very similar to some bacterial genera known on Earth: *Siderococcus*, *Sulfolobus*, but also filamentous colonial forms, such as *Phormidium frigidum* [23]. Yet, there is the possibility that the rocks where these fossils were found are, in fact, terrestrial rocks, reaching the Moon as meteorites [24].

The situation of potential extraterrestrial microbes is made even more complicated by insufficient knowledge of a potentially significant part of Earth's biosphere: nanoorganisms.

If you take a look at (Fig. **10.2**), you will see that something does not fit into the phylogenetic tree of life. LUCA, defined as the closest common ancestor of all known organisms, already had a typical prokaryote cellular structure, with DNA as genetic material (although there are also some diverging opinions) and with ribosomes of prokaryote type (these are the organelles responsible for translating genetic information into constitutive proteins).

But what was there before LUCA? And where do viruses fit? Strictly parasitic entities, lacking their own metabolism, were considered for a long time as either genetic elements that "escaped" from proper cells, becoming infectious, or even bacteria that evolved towards a totally parasitic life.

The discovery of some large-sized viruses, having DNA as their genetic material and a complex genome, including genes for aminoacid and protein synthesis challenged this view. Genetic analysis of mega viruses, mimiviruses, pandoraviruses *etc.*, shows that they are entities whose divergence goes prior to LUCA. Thus, new branches in the tree of life [11, 25, 26]!

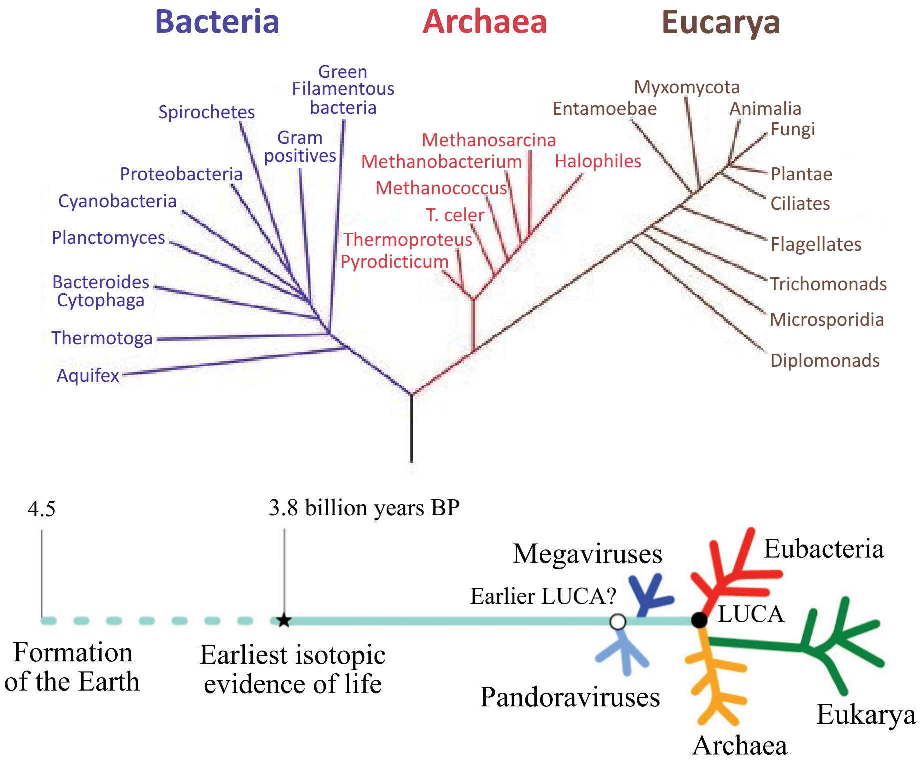

Fig. (10.2). The phylogenetic tree of life on Earth [10], starting with LUCA [11].

And, during the last few decades, new data emerged concerning the possible missing links. Under the name *nanobacteria*, scientists grouped together extremely small m-icroorganisms, observed through electron microscopy, in both mineral deposits (travertine, pyrite), and the human body, where, according to some researchers, they might be involved in abnormal mineralization processes in kidneys, teeth and circulatory system. The filamentous versions of these nanoorganisms were called *nanobes* [27 - 30].

They are, basically, entities measuring 0.02-0.15 µm, while we know that "typical" cellular life requires at least 0.10 µm! Just one ribosome measures 0.025-0.030 µm in diameter, and a normal cell has lots of them.

These entities often have a typical biological shape, rather than one similar to mineral crystals, that seem to contain DNA (although some researchers dispute this, suspecting external contaminations), and some even reported their multiplication on culture media. The microbiologists' opinions on nanoorganisms are extremely variated, ranging from "there is no such thing" to "they do exist, and they are the dominant life forms, constituting a numeric and quantitative majority of life on Earth" [31]!

Furthermore, microfossils reported in various meteorites, of Martian origin or not, seem rather similar, in terms of size and shape, to these nanobacteria and nanobes (Fig. **10.3**) [32, 33].

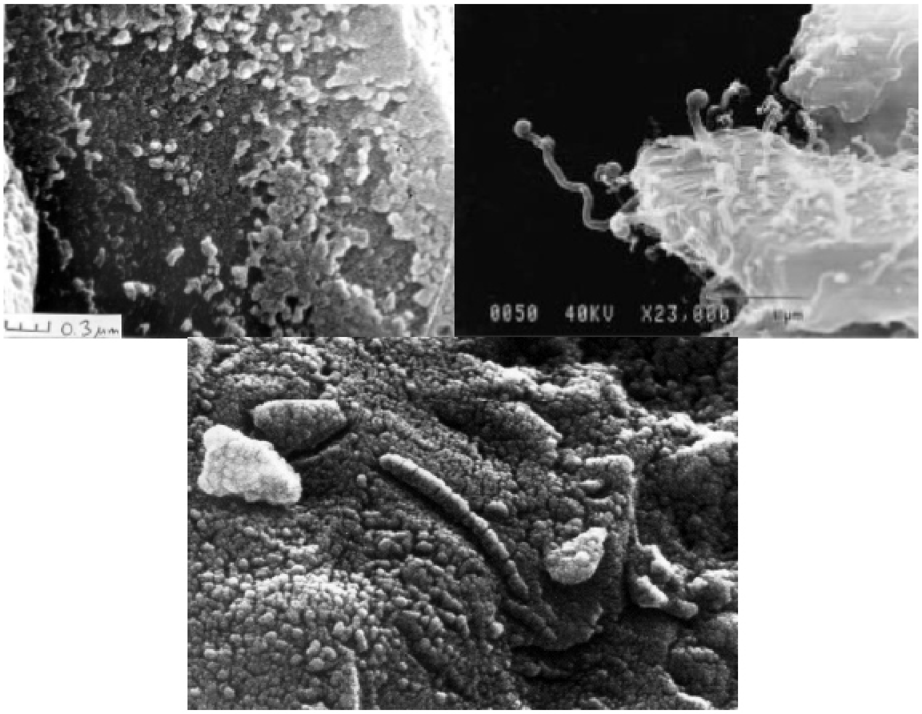

Fig. (10.3). Nanobacteria in pyrite deposits [29]; filamentous nanobes in sandstone deposits [31]; possible nanofossils in the Martian meteorite ALH 84001 [22].

Do nanoorganisms really exist (and, if so, could they have somehow reached neighboring planets, too)? We still don't know, but do not worry: up until recently, we knew nothing about archaea, for instance! This is how science progresses: slow but steady.

For the moment, you can weigh the pros and cons and form your own opinion, even if it may prove wrong. Surely, it is a bit disturbing: we might have missed the existence of some entire domains of terrestrial life; this is like not knowing anything about plants or animals, or even worse, since these unknown domains are likely to contain numerous biological kingdoms!

I personally consider that there are logical arguments favoring the existence of nanoorganisms. There have to be some missing links that precede cellular microbial life as we know it. Something to connect known organisms, viruses and the mineral domain. And the idea that all these "intermediate" organisms are entirely extinct is difficult to believe: could you imagine a complete extinction of bacteria, for instance?

Finally, there is the fourth big question, although you may find this the most bizarre of all. Are there Earthborn (human, most likely) civilizations that, sometime in the distant past, reached other worlds?

It is an interesting subject that, even more than those above, is mostly based on possibilities and speculation than on actual evidence. But it does not fit into the thematic of this paper, being rather the object of a discipline called Paleoastronautics, dedicated books and documentaries and even a book that I might decide to write.

Anyway, this is the least problematic issue, from an ethical point of view. Reuniting with our long-lost brothers in the Cosmos could only be a great perspective, as long as we avoid attitudes that could be interpreted as imperialism and take caution to reciprocal infections with dangerous pathogens (see the horrific plagues brought to the Americas by European settlers).

We can also assume that planets hosting independent, non-human alien civilizations (rather rare, if they really do exist) would be easy to spot, and their colonization should be avoided. It is always a good idea to avoid useless conflicts.

The much more likely possibility, invoked by opponents of terraformation and mass colonization, is that of encountering "primitive" life forms, mostly meaning micro- or nanoorgansims. Beings that would either share common origins with terrestrial life (this is almost exclusively possible within our planetary system) or independently evolved (this goes especially for other planetary systems).

From an extreme-conservationist point of view, any contamination and possible destruction of indigenous microbial life should be avoided, even if it means leaving an entire planet uncolonized! This is one of the main reasons why most space agencies have strict protocols for sterilizing scientific space probes (there is also a not very strict provision addressing this subject, in the United Nations' Outer Space Treaty – more precisely, the "*Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies*" – signed in 1967) [34].

However, this position faces four counterarguments, three practical and an ethical one.

First, the possibility of transpermia rules out, as we saw, the complete isolation of planetary biospheres, at least in our Solar System. Thus, even if we avoid contaminating and integrating them, this does not mean the process could not occur naturally!

Second, we have enough arguments to assume that the surfaces (meaning the very parts involved in terraformation and colonization) of neighboring celestial bodies are sterile. When we consider potential life forms on Mars, we actually mean bacteria that might live in deep groundwater. On the Jovian moons, life, if it exists, could only thrive in the mantle, at tens of kilometers beneath the surface.

Just on Venus, some theories mention a possible subsistence of a few micro-organisms from the planet's initial microbiota (if it ever existed) inside the sulfuric acid clouds [35]. Let's admit that this seems rather unlikely.

This means that terraforming will not affect local microbiota. Terrestrial life will settle the planetary surfaces, while indigenous life will still populate the depths. Even the purported Venusian bacteria would rather benefit from creating reasonable life conditions on the planet's surface!

Then, whatever we choose to do, it is extremely improbable to extinguish m-icroorganisms. Bacteria are ubiquitous! Even if we somehow tend to "uniformize" bacterial taxons, underestimating regional variety (for instance, we call *Escherichia coli* both a microbe isolated in a Canadian lake and one taken from a kangaroo's gut).

We can imagine panda bears going extinct (it would be sad, but possible). We can even imagine a mass extinction of all bear species on Earth (just as the dinosaurs vanished). But a total extinction of entire bacterial classes? It would be an event so extreme that it would make the planet uninhabitable: exactly the opposite of terraformation!

Finally, the ethical argument. You are surely aware of the numerous natural parks and reserves, some of which are mostly botanical and others zoological. But how many microbiological reserves do you know here on Earth? That's right, zero! Even the hydrothermal vents, the Movile Cave or the hot springs in Yellowstone Park are rather created to protect macroorganisms living on behalf of the local, unique microbiota.

Our society has no coherent policies for protecting terrestrial bacteria (this can be justified by the arguments above). So, why should we do otherwise on other planets?

Furthermore, are we willing to endanger the future of our species in the name of conservationism (some even invoke protecting inanimate landscapes)? And the future of life on Earth? We saw the negative consequences of stagnation, in the first chapter. The most radical one is total extinction at the end of our Sun's life cycle (or even earlier).

Note that, besides safeguarding our own species, we have another responsibility: protecting the Biosphere, in its entirety. Can we consider the whole biosphere as an organism? Without denying or underestimating the uniqueness of the human species and in parallel and not against the responsibility towards our own kind, there are strong arguments supporting this idea.

Each eukaryote cell (including those forming our body) is the result of an original symbiosis involving (at least) two different organisms: an archaeon (the likely source of the cell nucleus and much of its genome) and a bacterium. Two entirely different species, joined together to form a new one!

But each eukaryote cell also contains several organelles that originated as endosymbiotic bacteria. Mitochondria (organelles responsible for cellular respiration), plastids (hosting photosynthetic processes in algae and plants) and, possibly, others [36].

A step further, our organism hosts billions of bacteria belonging to different species: on our skin, in the intestines and in other cavities. They actually outnumber our own body cells and have their undeniable importance (which we remember, for instance, each time our gut microbiota is perturbed)!

We also know other types of symbioses, such as that between fungi and algae or cyanobacteria that form lichens. Yet, we usually forget an extremely important one: rhizospheric symbiosis.

In soil, root networks of plants, fungal mycelia, bacteria and some small animals work together in a harmonious and self-regulatory manner. Researchers found that communication systems link plant individuals and are mediated by fungi. This is so similar to hormonal or neural signaling systems inside our body [37, 38]!

Since such signaling networks extend throughout all the areas on Earth covered by soil and sediments, could we get a planetary "supraorganism”? This is what proponents of the *Gaia Hypothesis* think: the Biosphere is a single, huge organism, summing all the symbiotic relationships between individual organisms, ensuring the self-regulation of terrestrial environment. A planetary organism, in which cyanobacteria, algae and plants act as its "lungs”, decomposer fungi and bacteria are the "digestive system”, while animals are the "immune system”, maintaining the balance among primary producers and decomposers.

But, what is the place of *Homo sapiens* in this supraorganism? Maybe our function is to accelerate evolution (even if often in a destructive manner, in the short term). To unify ecosystems: by travelling all around the world, humankind carried along countless "opportunistic” species, thus altering and uniformizing habitats; even if this proved damaging for many indigenous species, which were unable to adapt, it could also be seen as a positive action when considering long-term evolution.

And even more important, we may have the role of propagules, of "spores” of our Biosphere. We are the only species able to systematically travel through interplanetary and, in the future, interstellar space.

In this context, the process of colonizing and terraforming other planets becomes an imperative: a way of expanding, reproducing and preserving the Biosphere in its entirety. And even, where possible, integrating and unifying planetary biospheres, in a single, cosmic one. Just as human tribes joined together, eventually forming nations and supranational entities, just as all life environments are now adjoined by our contribution, the same way we would unite life in the Universe. Few people will think of this as a negative outcome!

An even more serious reason for concern is that of reverse contamination: is it possible that indigenous alien organisms infect human colonists, causing lethal plagues? This is a subject often found in SF novels and movies.

Surely, we cannot completely rule out this possibility. While caution and prevention should accompany us wherever we go in this Universe, we need to know that the likelihood of such events to occur is extremely remote. Parasitism (this is all about in this case) implies long-term coevolution of the parasite with the host-organism or other related life forms.

Finally, another ethical aspect likely to draw criticism is that of using nuclear blasts on other planets. As we saw throughout the book, such explosions are indispensable to helioformation, terraforming Mars or the Moon.

Article IV of the same, aforementioned 1967 Treaty, states that "*States Parties to the Treaty undertake not to place in orbit around the Earth any objects carrying nuclear weapons or any other kinds of weapons of mass destruction, install such weapons on celestial bodies, or station such weapons in outer space in any other manner*" and that "*the establishment of military bases, installations and fortifications, the testing of any type of weapons and the conduct of military manoeuvres on celestial bodies shall be forbidden. The use of military personnel for scientific research or for any other peaceful purposes shall not be prohibited. The use of any equipment or facility necessary for peaceful exploration of the moon and other celestial bodies shall also not be prohibited.*" [39].

However, terraforming and helioforming processes do not violate any of the provisions above. They do not involve military actions or maneuvers, installing nuclear weapons into orbit or in extra-atmospheric space, but instead directing and detonating them on/beneath the surfaces of certain celestial bodies [40].

Also, note that there is a major distinction between a *nuclear weapon* and a *non-military nuclear explosive device*! "*Peaceful nuclear explosions*" (PNEs) are regulated by separate sections of international treaties regarding this kind of detonation.

They were used or just taken into account for use in large-scale excavations, releasing gas and oil amounts from subeconomic deposits, creating underground cavities for fuel storage, extinguishing fires on oil fields, energy production, facilitating the extraction of some metallic minerals, destroying large amounts of wastes, propelling spacecraft, destroying or diverting dangerous asteroids [41].

The difference is obvious: a weapon targets human beings (either military personnel or civilians) and infrastructure, while a non-military explosive will always be used against inert bodies, without affecting the human population in any way, in a transparent and consensual manner.

Thus, fully complying with the last provision of Article IV in the Outer Space Treaty, which does not forbid using any equipment or installation necessary for the peaceful exploration of extraterrestrial space.

CONCLUSION

There is no reasonable argument to prevent humankind from terraforming and colonizing other celestial bodies.

Encountering alien life is possible, but it would probably be rather scarce. Surely, we should avoid any type of conflict with any intelligent species (if there is such a thing) and refrain from the reckless destruction of non-intelligent life forms.

However, halting space expansion to protect extraterrestrial microbes or inanimate landscapes is not an option. Few things we can do would wipe out entire microbial biospheres, while coexistence is actually possible.

We need to keep in mind that our survival in the long term depends on us being able to go beyond our Solar system, thus avoiding cosmic disasters, overpopulation and resource scarcity. And it is more than just a fight for survival; it is a mission to spread earthborn life in all its forms and unify it with eventual local alien life to create a truly universal Biosphere.

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